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ODOR CONTROL BY SCRUBBING IN THE RENDERING INDUSTRY

Fats and Proteins Research Foundation, Incorporated

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16. ABSTRACT The report gives results of experiments conducted at a rendering plant to obtain data needed to design wet scrubber systems for rendering plant odor control. Scrubber performance was measured by both odor panel and gas chromatographic analysis. Experiments in a three-stage packed-bed laboratory-scale scrubber at the rendering plant evaluated solutions of sodium hydroxide and the strong oxidants sodium hypochlorite, hydrogen peroxide, and potassium permanganate. Since removal of 90% per stage was obtained with fresh alkaline sodium hypochlorite solution, this reagent was selected for subsequent longer-term tests. A 2-week test of a plant-scale horizontal spray scrubber, operating on plant ventilating air, showed odor removal of 83%. The outlet odor units averaged 64; the inlet ranged from 165 to 2500 odor units. A three-stage packed-bed scrubber was evaluated to replace an existing incinerator being used to treat a process air stream that contained from 5000 to 50,000 odor units. A week-long test with the scrubber gave a lower-than-expected average odor reduction of 85%. Further work is suggested to investigate conditions necessary to improve the results. Data was obtained on chemicals consumption and effect of flow variables on odor removal; these data were used to update computer models that can be used to design scrubbers for odor removal.

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ODOR CONTROL BY SCRUBBING IN THE RENDERING INDUSTRY

by

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FOREWORD

This report covers investigations performed by the IIT Research Institute (IITRI), Project C8243, under contract with the Fats and Proteins Research Foundation, Inc.

In this study, odor control in the rendering industry using wet scrubbers was investigated. Multiple-stage scrubbers with alkaline hypochlorite scrubbing solutions were tested in a rendering plant to control odorous emissions. Scrubbers offer an economic solution to odor problems. The information provided in this report will be a valuable aid in designing scrubbing systems to achieve specified reduction in odor levels.

Those who contributed to this project were: Dr. A. Dravnieks, J. E. Huff, Dr. R. H. Snow, W. Stepp, C. Swanstrom, and J. Whitfield of IIT Research Institute, and Dr. W. Boehme of the Fats and Proteins Research Foundation, Inc.

Data are recorded in Logbooks C21380, C21569, C21573, C21633, and C21911.

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Werner R Boehme

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INVESTIGATION OF ODOR CONTROL IN THE RENDERING INDUSTRY

ABSTRACT

Experiments were conducted at a rendering plant to obtain data needed to design wet scrubber systems for rendering plant odor control. Scrubber performance was measured both by odor panel and gas chromatographic analysis.

A series of experiments in a three-stage packed-bed laboratory-scale scrubber at the rendering plant evaluated solutions of sodium hydroxide and the strong oxidants sodium hypochlorite, hydrogen peroxide, and potassium permanganate. Removals of 90% per stage were obtained with fresh alkaline sodium hypochlorite solution, and this reagent was selected for the subsequent longer-term tests.

A two-week test of plant-scale horizontal spray scrubber operating on plant ventilating air showed odor removals of 83%. The outlet odor units averaged 64, while the inlet ranged from 165 to 2,500 odor units.

A three-stage packed-bed scrubber was evaluated to replace an existing incinerator being used to treat a process air stream that contained from 5,000 to 50,000 odor units. A week-long test with the scrubber gave an average odor reduction of 85%, lower than expected. Further work is suggested to investigate the conditions necessary to improve the results.

Data was obtained on chemicals consumption and effect of flow variables on odor removal, and these data were used to update computer models that can be used for design of scrubbers for odor removal.

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INVESTIGATION OF ODOR CONTROL IN THE RENDERING INDUSTRY

1. INTRODUCTION -- PREVIOUS WORK

The Fats and Proteins Research Foundation, Inc., and the U.S. Environmental Protection Agency have jointly sponsored a series of research programs to control rendering plant odors. One of the early studies resulted in the identification of many of the odorous compounds present in rendering plant air. This was accomplished by taking samples of air at rendering plants, separating the organic compounds into peaks by means of gas chromatography and identifying the peaks by means of mass spectroscopy. A computer regression analysis determined which of the peaks were correlated with the odor intensity of the samples, as independently determined by an odor panel. In this way, most of the odorous compounds were ascertained for the first time, and their chemical and physical properties were determined from handbooks. The important peaks and their identifications were listed in Report No. EPA-R2-72-088. They include various sulfides, disulfides (and probably mercaptans), C4 to C7 aldehydes, trimethyl amine and various C4 amines, quinoline, dimethyl pyrazine and other pyrazines, C3 to C6 acids. Other compounds are present but are not important so far as odor is concerned.

The objective of a second project was to develop an effective and economic means of odor control. Before undertaking laboratory experiments, known and potential odor control methods were compared based on limited data from the literature, and on reports of performance and costs from member companies of the Fats and Proteins Research Foundation. This comparison indicated that scrubbing was probably the most economic method, especially if one or more effective scrubbing reagents could be found. Incineration was also feasible, but was more costly for plant ventilating air. The study also indicated that commercially available control equipment was not designed on a reliable basis, partly because of the lack of quantitative data on the odorous compounds in rendering odors. Rendering companies were not in a position to rationally select from among the control equipment offered by manufacturers.

Computer design studies were performed, including calculations for capital and operating costs for odor control by incineration, and by packed bed scrubbers and horizontal spray scrubbers. The incinerator performance was assumed to be governed by an overall combustion reaction, the rate constants for which were determined as functions of temperature from available plant data. The design of scrubbers was based on the idea that reagents could be found that react rapidly with the odorants, so that the scrubbing process would be mass-transfer controlled. Based on these concepts, the computer programs were able to explore or optimize the operating conditions to find the design having minimum annual cost. Results of design and cost estimates for each control method were presented in Report No. EPA-R2-72-088 in tabular form for a series of air flow rates and odor reduction ratios. As a result of the information presented, we concluded that scrubbers offer the most economical odor control method for plant ventilating air, provided that effective scrubbing reagents can be found. At that time (1972), it appeared that incinerators might be competitive for a small, highly concentrated process air stream, but subsequent increases in fuel costs have since changed this conclusion.

The next steps in the investigation were to determine the performance of various candidate scrubbing reagents. The experiments were of an exploratory nature, and were conducted in the laboratory using the pure odor ingredients identified in the previous step of the project. A first series of experiments (called bubbler experiments) were designed to measure the ultimate reactivity of the reagents with no mass-transfer limitations. A second set of experiments measured the removal of odorous compounds from an air stream using a laboratory-scale, packed-bed scrubber. The scrubber was designed with sufficient mass transfer to reduce odors by 90%, assuming that the reaction rate is not limiting. Odor compound reduction was measured by gas chromatography.

Reductions of 80-90% were achieved with water for highly soluble odorants such as C4 amines and acids. Sodium carbonate was found to be no more effective than water, and sodium hydroxide gave only slightly higher removals. Sodium hypochlorite removed 90% of a number of odorants, including dipropyl sulfide and trimethyl amine. Potassium permanganate, another strong oxidizer, reacted slower but attacked some odorants not handled by hypochlorite. Hydrogen peroxide and sodium persulfate were comparable to hypochlorite. Sodium bisulfite removed 90% of aldehydes.

Based on the results of these experiments, it was determined that several of the strong oxidants should be evaluated as scrubbing reagents using actual rendering plant air.

2. SUMMARY

2.1 Objectives of Research Program

The objective of this program was to develop the necessary information to control rendering plant odors using wet scrubbers based on experiments with actual rendering plant air. The specific objectives of this program were as follows:

- to determine the most effective and economical combination of scrubbing liquids
- to obtain experimental data on the performance of scrubbers using actual rendering plant ventilating air, which typically contains between 100 to 1,000 odor units
- to develop computer models to assist in determining the optimum design for packed-bed and horizontal spray scrubbers based upon the experimental data collected
- The scope of the program was amended to include developing a scrubber system to handle high-intensity odors (5,000-50,000 odor units) that are presently treated by incinerators, and thus avoid problems of energy shortage and high cost of fuels required by incineration.

2.2 Odor Sampling and Analysis Methodology

A methodology for sampling and analysis of scrubber inlet and outlet air had to be established prior to testing scrubber performance. Two methods, sensory (odor panels) testing and gas chromatographic analysis, were used. The first method was already established (Dravnieks and Prokop, 1973) which utilized the collection of the odorous samples in thick-walled polyethylene bags and used the dynamic olfactometer for analysis. The gas chromatographic sampling method was developed on the previous project for plant air testing (Dravnieks, et al., 1971). To improve the accuracy of the results, this method was modified and tested in the first few months of the project. Small metal samplers, fitted with chromatographic adsorbent material, were developed for collecting the gas chromatographic samples.

The measurement of odors presents special difficulties, and it cannot be carried out with the accuracy expected in usual analytical chemistry work. Odor panel measurements with butanol have shown an accuracy of ±30%, but the results in this report with rendering plant air appear less accurate than this. A few repeat tests have fallen within the range of a factor of 2. In the case of gas chromatography, the measurements with pure compounds were found to be reproducible within 29%. The reproducibility with the same rendering air sample is similar. However, with different rendering plant air samples, the relative amounts of various peaks changes from sample to sample; since the peaks may overlap, it is difficult to determine the baseline for graphical integration. From observing the variations of individual peaks within the chromatograms, we estimate that the chromatograph data has about the same accuracy as the odor panel data.

The only way to establish the accuracy of the plant measurements is to repeat each odor removal test and statistically analyze the data; not enough repeat experiments were done to permit such an analysis of the data.

However, the reliability of the results is increased by combining the results from both methods. For example, if the standard deviation of odor measurement by each method is a factor of 2, or a 34% chance that the error is more than a factor of 2, then the probability that the error of both methods of measurement exceeds a factor if 2 is 0.34 x 0.34, or 12%. This means that 88% of the time the error will be less than a factor of 2. Thus, a 90% removal (10% odor residual) will have an 88% chance of lying between 80 and 95% odor removal (5 to 20% odor residual). To increase the accuracy of the results will require carrying out many more repeat odor removal measurements. In many cases, the agreement between the two methods was better than this, but in a few critical cases, it was comparable to this example.

2.3 Determination of the Optimum Scrubber Reagent Combination

A three-stage, full-scale horizontal spray scrubber and a three-stage, laboratory packed-bed scrubber were used throughout this program. By using multiple stages, a different scrubbing reagent can be utilized in each stage. A series of tests were performed to evaluate the effectiveness of several scrubbing reagents and combinations thereof. Three different combinations resulted in odor removals of over 98% when scrubbing the high-intensity odors (5,000-50,000 odor units) with the three-stage packed-bed scrubber. Reagent life tests were performed on all three combinations to ascertain which combination was the most effective. The results of these tests indicated that multiple stages of alkaline sodium hypochlorite gave the highest odor removal (96% through a two-stage packed-bed as compared to 77% and 89% for the other two combinations) at a lower cost than other scrubbing combinations.

2.4 Full-Scale Plant Scrubber Tests

The final step in this program was the testing of the performance on plant ventilation air of the plant horizontal spray scrubber with the selected reagent combination over a two-week period. The plant scrubber was modified to add sodium hypochlorite and water continuously to the system, and to bleed off a small fraction of the scrubbing solution to the sewer continuously. This test was performed during the hottest two weeks of the year, providing severe test conditions.

Throughout the test period, no odor complaints were received from the surrounding community, confirming satisfactory performance of the scrubber. The reduction in odor level averaged 83% (92% if one test is excluded where we believe the effluent contained a chlorine odor) while the gas chromatographic results showed an average reduction in odorant concentration of 85%. The outlet odor level averaged 64 odor units for the entire test, while the inlet ranged from 165 to 2,500 odor units.

2.5 Scrubbing of High Intensity Odors

As an additional objective of this program, the feasibility of treating incinerator inlet air streams with packed-bed scrubbers was determined. Preliminary tests on the laboratory packed-bed scrubber demonstrated that removals of 90% per stage could be obtained with fresh alkaline hypochlorite solutions. Additional tests indicated that odor removals of 88% per stage could be achieved after many hours of scrubbing, even when the hypochlorite concentration had decreased 75%.

A week-long laboratory packed-bed test was conducted at the plant to collect performance data on the continuous make-up and blow-down system. The performance of the scrubber was considerably below the anticipated level, since the average odor component reduction was only 85%. The reasons for the lower than anticipated removals were attributed to the following problems: (1) blow-down rate was initially set too low; (2) caustic addition rate was initially set too low, resulting in lower than required pH levels; and (3) air temperature, which reduced the capacity of the scrubbing reagents. Problems 1 and 2 were partially corrected during the week-long test, and the scrubber efficiency was improving near the end of the test, 98 and 79% removal compared to 59 and 34% for the first 2 measurements. Considerable data was obtained from this test needed for completing the computer design model for packed-bed scrubbers.

2.6 Computer Design Models and Calculations

Computer design models were developed during the previous program (Report No. EPA-R2-72-088) for horizontal spray scrubbers and packed-bed scrubbers. Using the new results from the scrubbing tests performed at the rendering plant, the mass transfer equations were checked and improved to agree with the plant scrubbing data. The predicted residual odors should be within the accuracy of the measurements (a factor of 2). The cost information was also revised and expanded to agree with current practice in construction of scrubbers. Such preliminary cost estimates are expected to be accurate within 30%. A series of design calculations was then carried out for typical plant conditions. The results from the computer models provide the rendering industry with the necessary design and cost information for selecting scrubber systems. From these models, scrubbers can be designed to achieve a specified reduction in odor level within the limits of test results.

2.7 Activated Carbon Alternatives

For achieving extremely low odor levels, the use of activated carbon was evaluated. The cost of using carbon without regeneration was estimated, and found to be more expensive than scrubbing, even for low inlet odor levels of 100 odor units. For normal plant ventilating air with an odor level of 100 to 1,000 odor units, the cost of carbon would be even higher. If regional carbon regeneration plants become available, carbon as a polishing step will be more attractive.

2.8 On-Site Generation of Sodium Hypochlorite

The economics of on-site generation were also developed. For rendering plants currently purchasing sodium hypochlorite, on-site generation provides an alternative. The use of chlorine gas and caustic for preparing the alkaline sodium hypochlorite solution is typically 15% more economical than on-site generation in most parts of the country. Future price increases in chlorine gas will improve the relative economics of on-site generation.

3. DESCRIPTION OF THE LABORATORY AND PLANT SCRUBBERS

Two scrubbers were used throughout this program to evaluate different scrubbing liquid combinations, and to determine the effect of various operating conditions on performance. A counter-current packed tower designated the "laboratory scrubber" and a horizontal spray scrubber known as the "plant scrubber" were used throughout the test program.

3.1 Laboratory Scrubber

A three-stage laboratory scale, counter-current packed bed scrubber was designed, constructed, and installed at the rendering plant in Des Moines, Iowa. (The laboratory scrubber used on the previous project comprised one stage of this system.) The system was designed to determine the performance of a variety of combinations of scrubbing liquids and to provide data on mass transfer rates. The scrubber was constructed so that all three columns could be operated in series, or the last two columns could be operated in parallel. The experimental scrubbing system with the last two stages connected in parallel is shown in Figure 3-1. Initially, 4-ft long, 6-in. diameter glass columns were installed with 2 ft of packing in each column. The packing used throughout this project was 1/2-in. Intalox saddles. For the last phase of the project, the 4-ft columns were replaced with 6-ft columns, and the packing depth in each stage was increased to 4 ft. The scrubbing liquids were placed in 25-gal polyethylene drums. Polyvinyl chloride (PVC) pipe was used for both the gas and the liquid piping. The gas flow rate was measured by an orifice with a manometer. Typically, 17 cfm of gas was passed through the scrubber, and each scrubbing solution was circulated at 0.6 gpm.

Odorous air for the laboratory scrubber was obtained from two sources: the inlet to the plant scrubber, and the inlet to the incinerator which handles the cooker noncondensibles

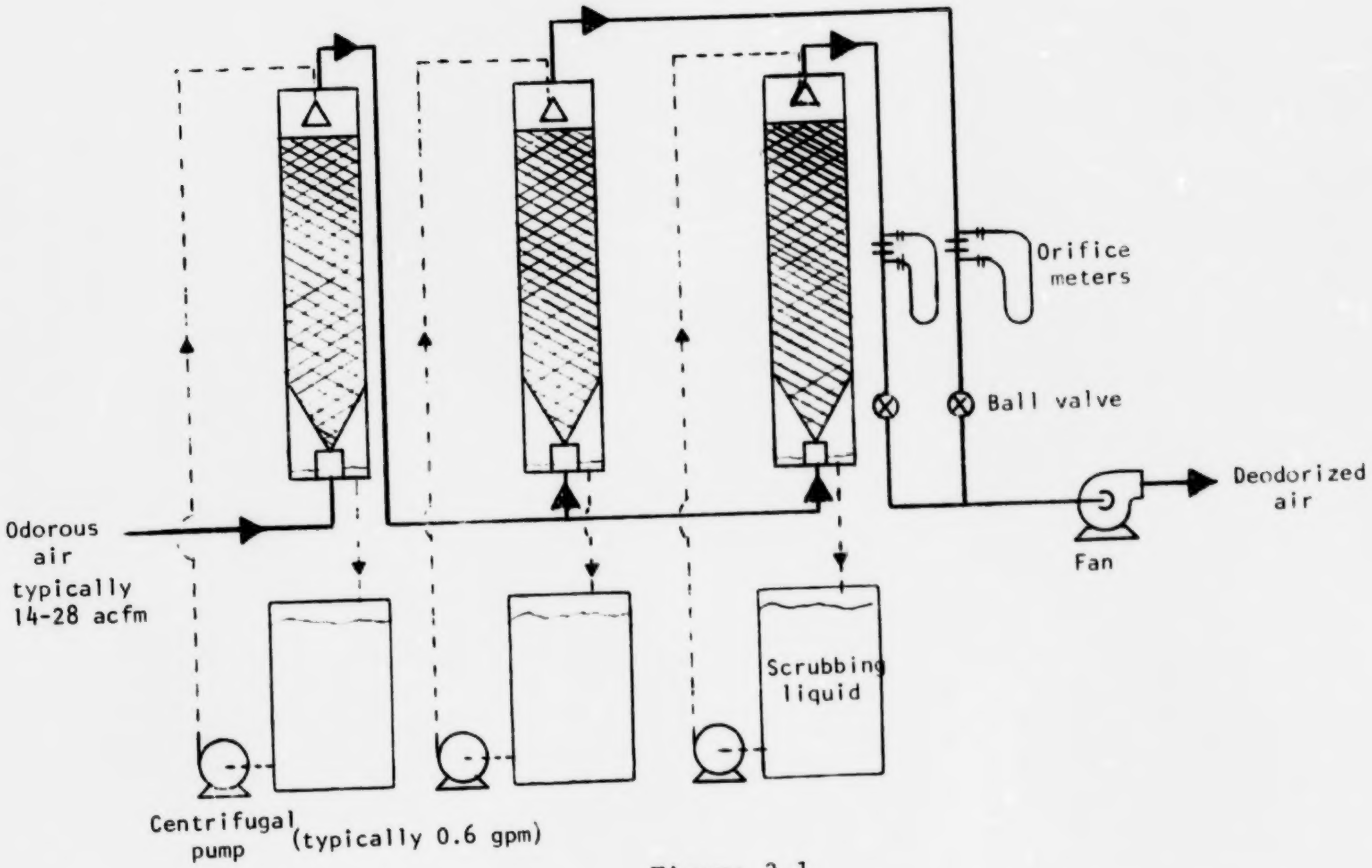
Odorous air typically 14-28 acfm
Centrifugal pump
(typically 0.6 gpm)
Scrubbing liquid
Orifice meters
Ball valve
Fan
Deodorized air

Figure 3-1

LABORATORY PACKED-BED SCRUBBER

and continuous cooker shrouding off-gases. Either air source was connected to the laboratory scrubber using 4-in. polyethylene pipe. Usually, the incinerator inlet stream (process air) ranged from 5,000 to 50,000 odor units, while the plant scrubber inlet stream (plant ventilating air) ranged from 100 to 1,000 odor units.

3.2 Plant Scrubber

The rendering plant at Des Moines, Iowa, has a full-scale horizontal spray scrubber designed by Air Conditioning Corp., Greensboro, North Carolina.* This scrubber is a three-stage unit that treats approximately 67,000 acfm of plant ventilating air. (This flow is based on actual velocity measurements.) This type of scrubber has been installed in a number of rendering plants. A drawing of a one-stage scrubber is shown in Figure 3-2.

Approximately 275 nozzles provide a relatively coarse spray in each stage. The nozzles are arranged in banks, with all the nozzles facing directly into the flow of air. A single fan is located after the first scrubbing stage. Each stage has a mist eliminator to minimize entrainment of scrubbing solution from one stage to the next. Separate scrubbing solution tanks are provided for each stage; however, the second and third stage tanks are also used by another similar horizontal spray scrubber located on the roof of the plant. The second spray scrubber is only used during the hottest part of the year to increase the flow of plant ventilation air. The liquid piping is all made of PVC, while the shell of the scrubber contains type 304 and type 316 stainless steel.

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*Tradenames are mentioned for identification purposes and not to endorse any particular product.

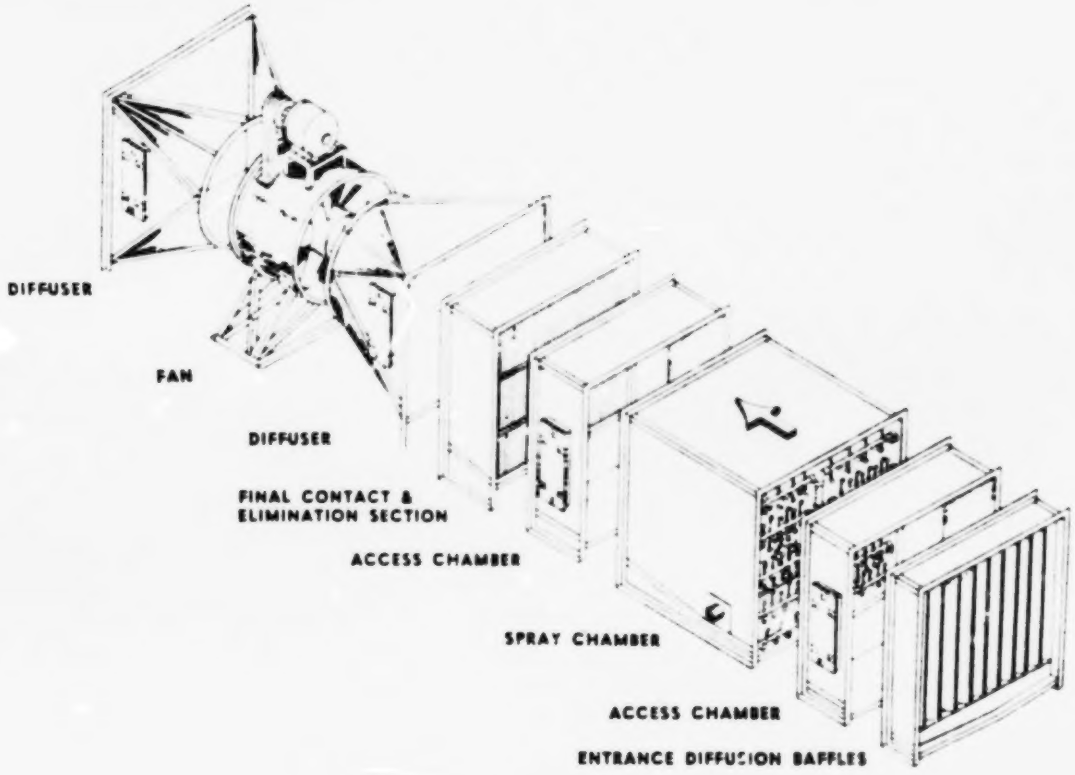
DIFFUSER
FAN
DIFFUSER
FINAL CONTACT & ELIMINATION SECTION
ACCESS CHAMBER
SPRAY CHAMBER
ACCESS CHAMBER
ENTRANCE DIFFUSION BAFFLES

Figure 3-2

ONE-STAGE HORIZONTAL SPRAY SCRUBBER

4. DESCRIPTION OF ANALYTICAL TECHNIQUES

In order to determine the most effective scrubbing combination and to evaluate the effect of different operating parameters, a series of comparative tests was performed. The efficiency of the scrubber had to be measured in order to ascertain the most effective scrubbing system.

To determine scrubber performance, a quantitative method of odor measurement based on previous work was selected. The following two methods were used throughout this program:

- odor panel measuring the subjective odor intensity
- gas chromatograph measuring the concentrations of known odorous compounds.

The gas chromatograph techniques used in the previous project were modified for field measurements. The recovery of transfer from the chromatographic samplers was improved from 60% to 90%, when measured with pure compounds. The sampling procedure and odor identification methods, which are considered a significant advance in odor measurement, are discussed below.

4.1 Field Sampling Procedure

Since all scrubber testing was performed at the Des Moines rendering plant and samples were analyzed in Chicago, procedures for collecting, transmitting, and analyzing odor samples were developed. Bags of odorous air for the odor panel and gas chromatograph (GC) samples were collected for each test. This required the development of sampling probes.

For the plant scrubber, 4-ft long sampling probes were constructed with small ports along the entire length of the probes. A diagram of the sampling system is presented in Figure 4-1. Except for the inlet sample probe, a demister was required for all probes because of the possibility of entrained water in the gas stream. From the demister, the

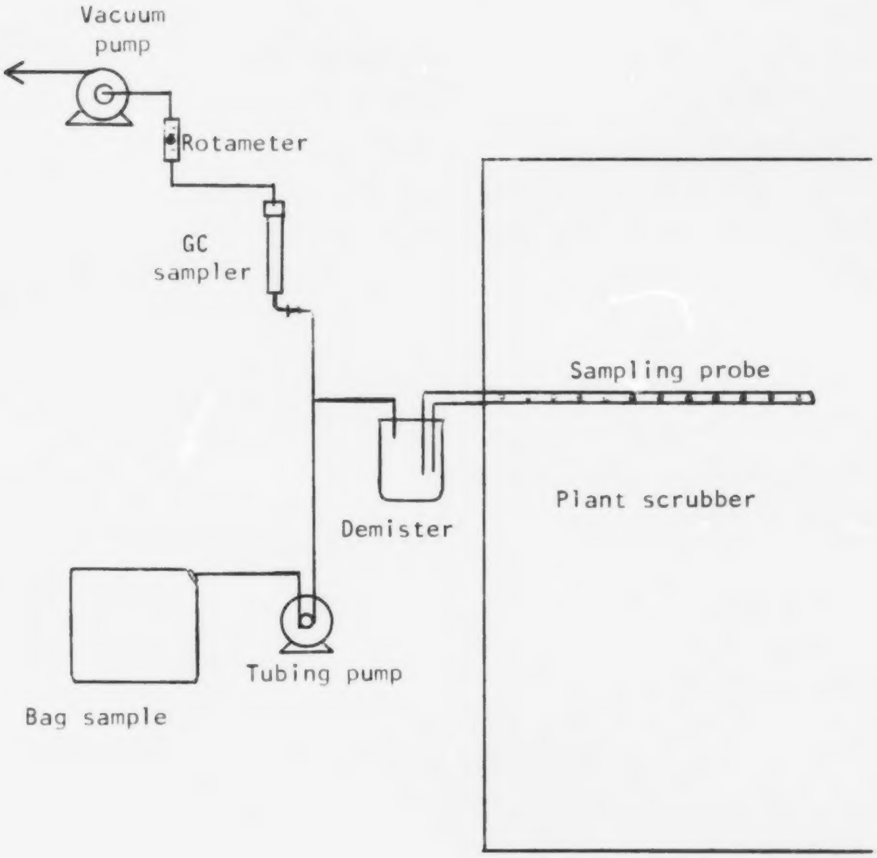
Vacuum pump
Rotameter
GC sampler
Sampling probe
Plant scrubber
Demister
Tubing pump
Bag sample

Figure 4-1

FIELD SAMPLING SYSTEM

gas stream was split into two portions. Part of the gas passed through a peristaltic pump into the sample bag, while the remaining gas stream passed through a GC sampler, a rotameter, and a vacuum pump.

A timer was used to activate a common vacuum pump which pulled the gas through all of the GC samplers for the same period and length of time. All bag samples were collected simultaneously with the GC samples.

In the laboratory scrubber, no special sampling probes were required. The samples were obtained from the 1-1/2-in. diameter PVC pipe used to pass the gas stream between the scrubbing stages. No entrained moisture was found in the laboratory gas streams, and so no demisters were necessary. Bag samples were collected at all sampling points simultaneously with the GC samples.

4.2 Sensory Odor Determination

One method of ascertaining odor removal efficiencies utilized the odor panel. The methods of sampling and measurement have been described (Dravnieks and Prokop, 1973). Techniques for sampling and evaluating these samples are summarized here. The samples for the odor panel were collected in 20-liter (0.67 ft^3) thick-walled polyethylene bags. Prior to actually taking the samples, the peristaltic pumps were started and the bags partially filled. The bags were then emptied and the sampling begun. This initial filling and flushing permitted odor adsorption onto the container walls prior to the actual sampling. This conditioning technique stabilized the odor intensity of the gas samples until the bags were analyzed.

The gas samples were transferred from the steel sampling probe to the polyethylene bags through food-grade Tygon tubing. The Tygon tubing also adsorbed odorous compounds, and the initial filling and flushing of the bags conditioned the tubing. Replacement of the Tygon tubing was necessary after two to four tests, and also after every sampling of the incinerator inlet stream.

The collected gas samples in the polyethylene bags were utilized for determination of odor intensity by the dynamic method developed by Dravnieks and Prokop (1973). The results were expressed in terms of ED_{50}, which is the number of dilutions at which 50% of the panelists begin to detect odor during the dynamic test.

4.3 Gas Chromatograph and Sampling System

In a previous project (Burgwald, et al., 1971), a gas chromatograph procedure and sampling system were developed for identifying the odorous components of plant air.

In the earlier project, the gas was passed through a sampler containing 5 g of Chromasorb 102 adsorbant in a stainless steel collector tube. The adsorbed odorants were than transferred to a chilled tube, and then into the chromatograph column. This method pre-concentrated the sample, and resulted in a higher sensitivity of analysis; however, there was a question as to the quantitative transfer ability from the adsorbant to the chilled tube and then to the chromatograph.

In the present project, the previous method was modified to make the transfer operation more quantitative. A smaller stainless steel collector tube was developed, and the sample was transferred directly to the chromatograph by electrically heating the walls of the collector. This method resulted in a simpler, more controllable transfer operation, and is discussed in the following paragraphs.

4.3.1 GC Sampler Design

The first GC samplers constructed were 3/8 in. diameter by 6 in. long. Heat transfer from the sampler walls to the packing was too slow, resulting in poor separation of the peaks. For more rapid heating, 1/4-in. thin-wall, stainless steel tubing 12 in. long was fabricated into samplers. These samplers heated rapidly, but resulted in excessive pressure drops when sampling the scrubbers. The final samplers were made of 5/16-in. tubing, 8 in. long, with 0.010-in. thick walls. These contained the same amount of adsorbant, 2.8 gm, but had only half as much pressure drop as the 1/4-in. samplers. A diagram of the GC sampler is shown in Figure 4-2.

Breakthrough tests were performed by connecting two GC samplers in series and passing 10 ℓ of rendering plant air through the samplers. The second sampler connected in series contained only small quantities of the lighter molecular weight components (less than 2% of the quantity found in the first sampler).

Initially, the GC samplers were packed with Chromasorb 102, but various components from this adsorbant were found to bleed off during the transfer operation. This resulted in reduced senstitivty of the chromatograph. Tests performed with Poropak Q resulted in 90% less bleed-off compared to tests with Chromasorb 102. Thus, except for the first batch of plant tests, Poropak Q was used in the GC samplers.

To assure removal of all measurable material before reuse, the samplers were conditioned at 185°C in a laboratory oven for a minimum of 12 hours while passing nitrogen through the samplers. Periodic checks were made on the cleaned samplers before reusing. No gas chromatograph peaks were observed from the cleaned samplers.

4.3.2 The Gas Chromatograph System

The chromatograph used in this program was a Victoreen two-column Model 3000-2. Initially, two 10-ft 1/8-in. diameter columns were used. After a few tests, the 10-ft columns were replaced with 20-ft columns to obtain better

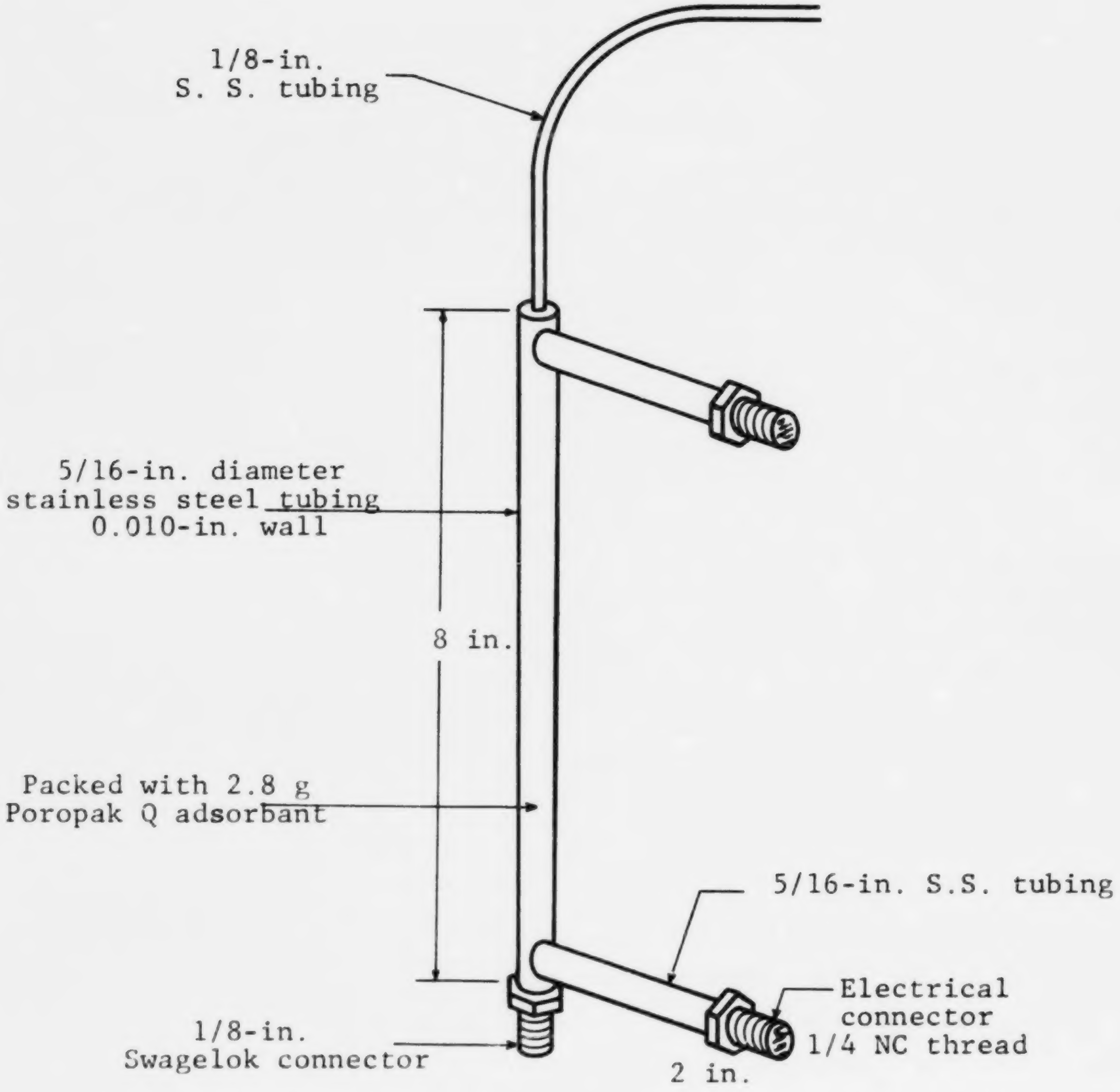
1/8-in.
S. S. tubing
5/16-in. diameter
stainless steel tubing
0.010-in. wall
8 in.
Packed with 2.8 g
Poropak Q adsorbant
5/16-in. S.S. tubing
Electrical
connector
1/4 NC thread
1/8-in.
Swagelok connector
2 in.

Figure 4-2

CHROMATOGRAPH SAMPLER

separation of the many peaks found in rendering air. The chromatograph was further modified by inserting a stainless steel heat shield with a stainless steel cooling water coil silvered-soldered to the shield. This modification allowed the temperature programming to start at 30°C instead of 60°C, resulting in improved separation of the lighter molecular weight compounds. The lower portion of the chromatograph recorder trace was spread over a 12-min interval compared to a 2-min interval previously.

The procedure for injecting a sample from the odorant collector was also optimized by a trial process. The temperature of sample transfer from the GC samplers to the chromatograph column was critical.

A trade-off is involved in selection of the transfer temperature. We found that at a temperature of 180°C, the compounds having molecular weights up to at least C20 (as previously identified by mass spectrograph) were eluted. At higher temperatures than this, some bleed-off from the sampler was produced even when no sample was adsorbed, suggesting that erroneous signals would beproduced by heating to a higher temperature than 180°C.

The procedure that evolved is as follows: (refer to Figure 4-3) with the oven cooled to 20°C, clear the GC sampler connector tube of air by passing helium through the sampler. Then attach the sampler to the helium tube. Attach the electrical heater leads and thermocouple controller to the sampler. Insert the sampler exit tube into the injection port using the Conax fitting on the port. The helium carrier gas stream is still entering the chromatograph via a tee at the injection port. Wait until the system becomes pressurized and the recorder output is stable -- 5-10 minutes. Then, almost simultaneously do the following four operations: (1) switch the helium carrier gas through the sampler; (2) turn off the cooling water solenoid valve; (3) start the chromatographic

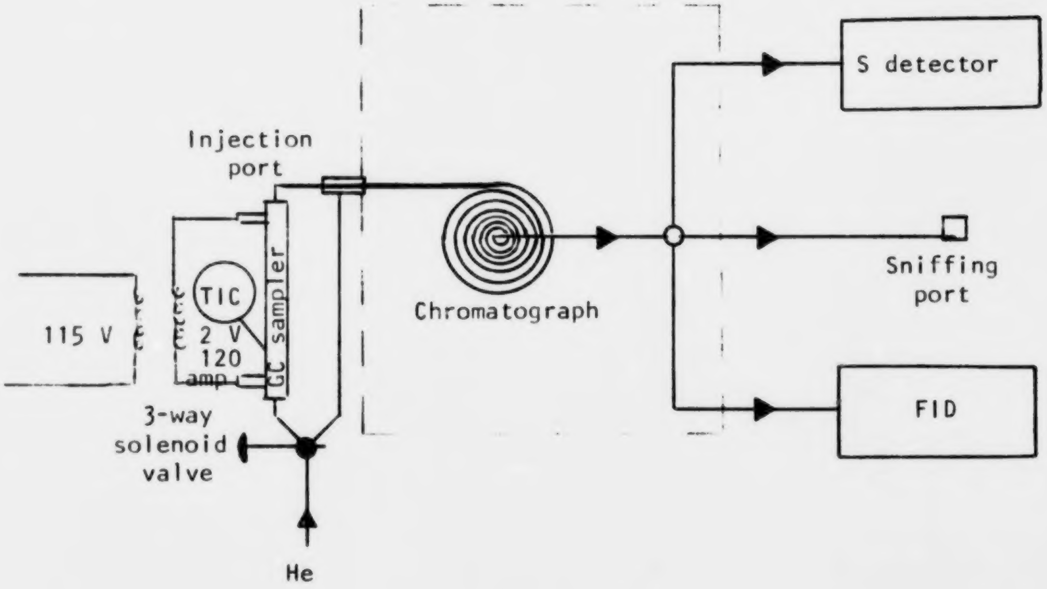
S detector
Injection
port
Chromatograph
Sniffing
port
FID
115 V
TIC
2 V
120
amp
GC sampler
3-way
solenoid
valve
He

Figure 4-3

CHROMATOGRAPH SAMPLING AND ANALYSIS SYSTEM temperature programmer beginning at 0°C at a rate of 4°C/min; and, (4) turn on the sampler heating system switch. The sampler heater variac is preset so that it requires 2 min for the sampler to reach the set point of 180°C. Continue operating the system until the chromatograph programmer reaches its set point of 200°C.

As a result of the procedure outlined above, the initial pressure peak due to opening the system to connect the sampler is completed before the sample was transferred to the column. Furthermore, the rate of heating of the sampler is slow enough so that changes in the volume of gas in the sampler due to heating have little effect on chromatograph performance. The samples are transferred to the column before the programmer reaches the actual starting temperature of 30°C. At this temperature, the column can adsorb and hold all the odorants that are of importance (except gases such as NH_3 and H_2S).

Several other modifications were necessary during the early part of the program to improve the quality of the chromatograms. The line from the chromatograph to the Tracor sulfur detector had to be heated to prevent condensation of the components in the line. A sniffing port was also installed which aided in the identification of the odorous components. The accuracy of GC results was discussed in Section 2.3 above.

4.3.3 Odorant Calibration and Accuracy of GC Measurements

The identification of odorous compounds present in rendering plant air was reported in a previous project (Report No. EPA-R2-72-088). Because the chromatograph procedure was modified in this project to improve quantitative measurement, the peak positions changed, and the new peak retention times for the odorous compounds had to be identified on the chromatograms. This work was completed by injecting known compounds into both chromatographs and comparing the time required before the compound was detected by each flame ionization detector. Using this procedure, each of the key odorous components were identified on the new chromatograms. The peak area for different quantities of odorants was determined by injecting known concentrations of compounds into the chromatograph and measuring the area of the response. Monthly, the calibration was checked by injecting known concentrations of different components and measuring the response. The calibration was used to convert peak area to μg of odorant.

A computer program was used with a Hewlett-Packard desk computer to integrate the peak areas and multiply by the calibration factor and sample size factor. The area was read into the computer by moving a sensor over the chart recorder trace of the peak, after first drawing in the estimated baseline of the peak.

Calibration runs with known amounts of pure compounds were made at various times during the development of the chromatographic procedure. In one case, 13 determinations were made using n-propyl sulfide samples, giving a mean calibration of 704 in. sq. of recorder chart per μg n-propyl sulfide, with a standard deviation of 203, or 29% of the mean. One another day, 5 determinations were done with n-propyl sulfide giving a mean of 1,788 and a standard deviation of 105; and 3 determinations were done with amyl alcohol giving a mean of 1,261 and a standard deviation of 32. In this project, we are concerned only with the relative error, since in each experiment, we are comparing the percent reduction of the outlet versus the inlet concentration to the scrubber. The standard deviation of 29% can therefore be taken as a measure of the relative accuracy that can be expected from these measurements.

Rendering odors comprise a complex mixture of compounds that cannot be completely resolved into peaks with a reasonable amount of effort. For example, the sulfur detector sometimes showed a peak from a sulfur compound, while the flame ionization detector showed only background signal or a peak that was partially obscured by peaks from other compounds. The success of making chromatographic measurements on rendering odors depended on being able to identify selected peaks in the chromatogram, even when the relative intensity of the various peaks changed from sample to sample, and even when the elution time of the peaks changed by as much as a minute from sample to sample. Without the sulfur detector, it would have been impossible to identify the peaks in this way; with the detector, there were sometimes ambiguities, but the smaller number of sulfur peaks made identification easier. The only measure we have of the accuracy of the rendering odor measurements made with the chromatograph is the apparent consistency of the overall results of the scrubbing experiments. This can be judged by examining the tables of results, but we do not have any independent measure of accuracy other than the calibration tests with pure compounds.

In spite of these limitations, the chromatographic results were valuable as a check on the odor panel data, and especially to explain some of the results of the scrubbing experiments. This is discussed below, in the presentation of experimental scrubber results.

4.4 Analyzing the Gas Chromatograms

Up to 16 peaks were identified from each chromatogram and the concentration of each determined. Each odorous compound contributes to the over-all odor level, but ascertaining each individual contribution is a monumental task. Ideally, the odor contributions from each compound could be added together to ascertain the total odor level; however, only 9 of the 16 compounds have been identified and the effect of interaction between the compounds on the over-all odor level is also not known. Thus, it was not possible to assign a fraction of the over-all odor level to each of the compounds present. If one assumes that the threshold odor level for each compound is approximately at the same concentration, then the inlet and outlet concentrations could be added and a single percent removal determined; however, the threshold odor levels vary by more than a factor of 1,000, and this method would result in the two or three highest concentration compounds determining the entire reduction in odor level. In other words, the low concentration, extremely odorous compounds, would have no influence on the calculated removals.

In order to provide equal weight to each of the odorous compounds, the removal of each compound was determined. Then, all of the individual percent removals were averaged to provide a single average percent removal of odorous compounds. Ideally, in assessing the effect of compound removal on odor removal, one should weigh each compound by its contribution to odors. We know from the previous project which peaks are correlated with odor panel results (Report No. EPA-R2-72-088), but the correlation data are not quantitative. Therefore, we applied a weight of 1 to each compound when averaging the removals.

5. ODOR CONTRIBUTION OF PARTICULATES

The plant air was tested to determine the odor contribution of the particulates present in the air. A preliminary test was run to demonstrate the equipment and procedure. The results from the preliminary test indicated that particulates contributed less than 8% of the total odor present in rendering plant air.

For the principal test, two Millipore filters were attached to probes positioned directly in the gas flow at the plant scrubber inlet. Two additional Millipore filters were also used to sample the outlet from the plant scrubber. The inlet to the plant scrubber contained 1,600 μg of particulates per liter of air. The outlet sample increased in weight by 3,300 μg/liter of air sampled. Presumably the outlet sample contained considerable entrained scrubbing liquid, as the samples were not dried before weighing. This accounted for the weight increase.

To determine the odors associated with the particulates, the second set of Millipore filters were placed in polyethylene bags. The bags were then inflated with nitrogen gas from a lecture bottle. The use of nitrogen eliminated the possibility of obtaining an odorous air source in filling the bags. The odor panel found only one odor unit in the inlet particulate sample, as compared to a scrubber inlet air odor level of 150-360 odor units. The outlet particulate sample contained 15 odor units, as compared to an outlet air odor level of 35-50 odor units.

The very low odor level of the particulate inlet sample indicates that only a very small amount of the odor can be attributed to the particulates. The higher outlet particulate odor levels strongly suggest that the scrubbing solution droplets trapped on the filter impart some odor. This odor could be due to both sodium hypochlorite and odorous compounds that had accumulated in the scrubbing solution. More discussion of this outlet odor level is presented in Chapter 9.

6. EVALUATION OF SCRUBBING LIQUIDS

In order to optimize a wet scrubbing system, the most effective combination of scrubbing liquids must be found. Comparative scrubbing tests were performed using various liquids in both the laboratory packed tower and the plant spray scrubber. Considerable preliminary work in this area was accomplished in an earlier project (Report No. EPA-R2-72-088). The previous work is summarized, and the tests performed using actual rendering plant air are described below.

The objective of this part of the work was not to quantitatively establish the performance of each scrubbing liquid, but to compare them and determine which liquids merited further investigation on a more complete basis. "More complete" means repeating the experiments a number of times to establish a statistical measure of variation.

6.1 Previous Studies

The preliminary work (EPA-R2-72-088) used two types of scrubbing reaction studies with known odorous compounds. First, exploratory bubbler experiments were performed to determine the reagent capacity to consume the odorants. Second, a packed scrubbing column was used to measure the rate of reaction of the reagent with different odorants.

The previous laboratory experiments indicated that the following strong oxidizers are capable of reacting with those odorants which contain reactive functional groups: sodium hypochlorite, hydrogen peroxide, potassium permanganate, and sodium persulfate. For example, sulfides, aldehydes, and amines reacted with these oxidants. Quantitative results of the experiments are given in Report No. EPA-R2-72-088. The degree of removal of course depends on the configuration

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6.2 Initial Evaluation of Scrubbing Combinations

Because of the results from the previous project, most of the current test work concentrated on combinations using strong oxidizers. A total of six sifferent scrubbing combinations were evaluated at the rendering plant on plant ventilation air. A description of each combination is presented in Table 6-1.

Table 6-1

SCRUBBING LIQUID COMBINATIONS

Combination	First Stage	Second Stage	Third Stage
A	NaOH-pH 11	NaOH-pH 12	Cl_2, pH <7
B	NaOH-pH 11	NaOH-pH 12 + 1% NaOCl	1% H_2SO_4 + 1% H_2O_2
C	NaOH-pH 12 + NaOCl	NaOH-pH 12 + NaOCl	NaOH-pH 12 + NaOCl
D	NaOH-pH >11	NaOH-pH 12 + NaOCl	NaOH-pH 12 + NaOCl
E	NaOH-pH 12 + NaOCl	NaOH-pH 12 + NaOCl	NaOH-pH 12
F	NaOH-pH 12 1% NaOCl	NaOH-pH 12	1.5% $KMnO_4$

A list of comparative scrubbing tests using the plant horizontal spray scrubber is presented in Table 6-2. Because of potential corrosion problems with the aluminum fan after the first stage, the number of combinations that could be evaluated using the plant scrubber was limited, until the final test ,when the fan was coated with plastic.

Table 6-2

PLANT SCRUBBER COMPARATIVE SCRUBBING TESTS

Combination	Test No.	Date	Inlet ED_{50}	Outlet ED_{50}	Odor panel % removal	GC % removal
A						
Caustic Caustic Chlorine	2	9/18/73	330	150	55	-
	3	9/18/73	90	50	44	-
B						
Caustic Hypochlorite Peroxide	5	10/04/73	25	20	20	-
	6	10/04/73	30	20	33	-
	8	10/23/73	320	20	94	-
D						
Caustic Hypochlorite Hypochlorite	12	11/15/73	360	35	90	88
	13	11/15/73	150	50	67	-
	15	11/19/73	660	25	96	-
	16	11/19/73	300	70	77	70
	17	11/20/73	-	-	-	71

The rendering plant was using combination A when this program began. This combination was included in the tests to provide a comparison with future test work. The plant tests found combination A much less effective than combination D (removals of 44 and 55% compared to 90, 67, 96, and 77% in Table 6-2). The results from combination B using the plant scrubber were inconclusive because the inlet odor levels in Tests 5 and 6 were too low to obtain a good comparison. Test 8, however, gave a removal of 94% with combination B.

Because of the low odor levels frequently experienced with ventilation air in the plant scrubbers, most of the comparative scrubbing tests were performed using the laboratory packed bed scrubber. The laboratory scrubber could be fed with high intensity process air normally going to an incinerator. By using this odor source, the experiments could be continued during the cooler months of the year, and still have adequate odor levels to test the scrubber system (at least 300 odor units). The test results from the laboratory scrubber are presented in Table 6-3. As with the plant scrubber tests, combination A was found less effective in reducing the odor intensity (removals of 54 and 64%). Combinations B, C, E, and F all gave removals in the range 98 to 99.9%, except for one test where the inlet odor was only 15 odor units. The results in one test with combination D were unusually low (21%, although the chromatograph showed 81% in one test).

Based upon the initial comparative tests, three different combinations (B, C, and E) were found to be equally satisfactory. Because of the variable inlet odor levels, the results did not allow a ranking of the scrubbing liquid effectiveness of these three combinations. Thus, it was difficult to determine the optimum combination. This experimental problem was solved by developing a parallel scrubbing test procedure, which provided a direct comparison of reagents.

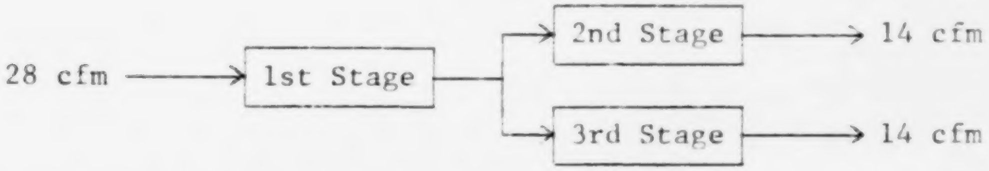
Table 6-3

LABORATORY SCRUBBER COMPARATIVE SCRUBBING TESTS

Combination	Test No.	Date	Inlet ED_{50}	Outlet ED_{50}	Odor panel % removal	GC % removal
A						
Caustic	2	9/18/73	330	120	64	-
Caustic	3	9/18/73	65	30	54	-
Chlorine						
B						
Caustic	5	10/04/73	15	10	33	-
Hypochlorite	7	10/04/73	17,000	45	99.7	-
Peroxide	10	10/23/73	34,000	460	98.6	98
C						
Hypochlorite	11	10/23/73	63,000	550	99.1	-
Hypochlorite	25	1/21/74	8,300	20	99.8	-
Hypochlorite	26	1/21/74	-	-	-	96
D						
Caustic	12	11/15/73	190	150	21	-
Hypochlorite	21	12/15/73	-	-	-	81
Hypochlorite						
E						
Hypochlorite	23	1/21/74	11,500	20	99.8	97
Hypochlorite	24	1/21/74	12,500	10	99.9	94
Caustic						
F						
Hypochlorite	28	1/21/74	4,500	75	98.3	67
Caustic	29	1/21/74	4,300	120	97	-
Permanganate						

6.3 Parallel Scrubber Life Tests

In order to obtain direct comparisons between different scrubbing liquids, the laboratory scrubber was modified so that the last two stages were operated in parallel, as shown below:



By operating with the last two stages in parallel, further evaluation of three-stage scrubber performance was not possible; however, without the direct comparison tests, the optimum combination could not be conclusively determined. All three combinations had demonstrated the capability to remove odorous compounds when the scrubbing solutions were fresh. By testing the scrubber performance under extended operation, an indication of the rate of oxidation, the holding capacity of the solutions for refractory compounds, and the potential odor from the scrubbing liquor (especially hypochlorite) could be ascertained.

In the first parallel scrubbing experiment, Test 31, combinations B and C were compared. The scrubbing test was performed over a 10-hr period to get a good indication of the performance and life of the two systems. The incinerator inlet air was used for the odorous source, but the odor level was considerably lower than anticipated. Over the 10-hr test, the hypochlorite concentration in the first stage only dropped from 1.1% to 0.99%. No drop was observed in the hypochlorite level or the hydrogen peroxide level in the final scrubbing stages.

The results from Test 31 are presented in the Appendix, Tables A-1 through A-5, and are summarized in Table 6-4. The

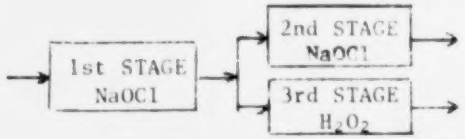


Table 6-4

SUMMARY OF SCRUBBING TEST 31
LABORATORY SCRUBBER

	1 → 2 stage					1 → 3 stage				
Sample round*	1	2	3	4	Avg	1	2	3	4	Avg
Odor ED_{50} inlet	700	-	15,500	590		700	-	15,500	590	-
outlet	25	-	45	45		265	-	370	175	-
	% removal					% removal				
Odor ED_{50}	96	-	99.7	92	96	62	-	98	70	77
GLC peaks										
1. Dimethyl sulfide	94	90	56	93	83	82	97	76	90	86
2. Pungent U.P. 90	98	97	84	95	94	79	89	56	86	78
3. Dimethyl disulfide	97	76	95	94	90	73	94	86	99.1	88
4. Butyric acid	92	86	63	71	78	84	99.0	81	88	88
5. Propylene sulfide (cabbage 880)	95	89	82	-	89	86	99.6	82	-	89
6. Bitter 655	98	87	90	96	93	70	76	73	78	74
7. Burnt 1233A (pyrazine)	97	71	-	74	81	70	94	-	64	76
8. Burnt 1233B (pyrazine B)	86	-	-	78	82	63	-	-	89	76
9. Rendering 1335	93	91	78	87	87	85	97	84	96	90
10. Fatty 1545	94	90	58	75	79	93	98	75	96	90
11. Burnt 1687 (quinoline)	96	82	-	60	79	55	99.3	-	97	84
12. Sulfur 660	-	-	-	-	-	-	-	-	-	-
13. Cheesy 2002	94	80	-	59	78	82	98.8	-	94	92
14. Unpleasant 2582	92	79	33	44	62	84	99.2	75	93	88
15. Fatty acid 1980	94	90	76	-	87	85	97	84	-	89
16. Fatty acid 2160	95	89	70	-	85	91	98.8	68	-	86
Average percent removal of each component	94	86	71	77	83	79	95	76	89	85

* Sample rounds 1 to 4 were collected at the following times: 1/4, 1.5, 3, and 9 hr, respectively.

chromatograph results indicate that the two scrubbing combinations are about equally effective. The H_2O_2 combination removed an average of 85% of each of the 15 odorous compounds, while the two-stage hypochlorite system removed an average of 83% of each of the compounds; however, the odor panel found the hypochlorite combination much more effective. The odor panel found a 96% average reduction in odor level in the hypohclorite combination as compared to only 77% reduction with the H_2O_2 combination. A careful review of the chromatograms found no new compounds or unusually large unidentified peaks. Tables A-1 through A-4 clearly show that the hypochorite combination is much more effective in removing two compounds, Pungent U.P. 90 and Bitter 655. The high levels of these two compounds in the outlet from the H_2O_2 combination could explain the higher odor levels observed.

Another possible explanation for the results might be that one solution allows certain refractory compounds to build up in the scrubbing liquor. To test this idea, fresh outside air was passed through the scrubbing system after the 10 hours of operation. The results from this test are presented in Table A-5. Prior to running this portion of the test, all the tubing for obtaining the bag samples was replaced with fresh tubing to minimize residual odors. The odor panel found 220 odor units coming from the H_2O_2 solution as compared to only 25 odor units coming from the hypochlorite solution. The chromatograms, however, indicated the quantity of most of the compounds bleeding off the hypochlorite solutions was greater than off the H_2O_2 solution, except for two compounds, Pungent U.P. 90 and Bitter 655. The higher odor level in the outlet from the H_2O_2 stage is probably attributable to these compounds, which are not effectively removed by the H_2O_2, or the formation of a new compound between the H_2O_2 and one of the odorous compounds which is not shown on the chromatograms. The test demonstrated that two stages of sodium hypochlorite with excess caustic is more effective than a stage of sodium hypochlorite followed by a stage of hydrogen peroxide with sulfuric acid. The use of two separate scrubbing reagents would increase labor costs for handling the solutions. Furthermore, hydrogen peroxide costs $0.26/lb (100%, 1973 basis), while chlorine costs $0.11/lb (1974 basis). Both materials can be hazardous to handle, but the use of one reagent limits the hazards to those of the one reagent; furthermore, chlorine is already in routine use in rendering plants. For these reasons, as well as the performance results, we decided not to conduct further experiments with hydrogen peroxide.

In the last experiment, Test 32, two stages of 1% sodium hypochlorite was compared to a stage of 1% sodium hypochlorite followed by a stage of 1% caustic. Prior to the addition of odorous air, clean air was pulled through the system and bag samples were collected on the outlets. The odor panel found very low odor levels, 12 and 10 odor units respectively from stages 2 and 3. This indicates there is very little residual odor in the piping and that little if any odor can be attributable to fresh scrubbing solutions.

Odorous air from the incinerator inlet was passed through the scrubber for a 24-hr period. The results are presented in Appendix Tables A-6 through A-10. Table 6-5 summarizes the results. The odor panel found an average of 97% reduction in odor level from the hypohclorite combination, as compared to an 89% reduction from the caustic combination. The chromatograms also indicated that the hypochlorite combination was more effective, showing an average component removal through the hypochlorite combination of 85% compared to a 71% removal in the caustic system. The multiple stages of sodium hypochlorite was found to be the most effective scrubbing combination.

From the chromatograms, it appeared that the caustic system was becoming saturated with certain compounds toward the end of the run. The removal efficiency decreased 15-20%, while no

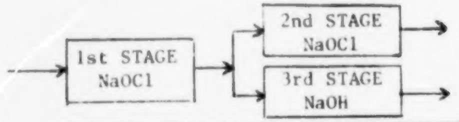


Table 6-5

SUMMARY OF SCRUBBING TEST 32 LABORATORY SCRUBBER

	1 → 2 Stage						1 → 3 Stage					
Sample round*	2	3	4	5	6	Avg	2	3	4	5	6	Avg
Odor ED_{50} Inlet	21,500	2700	5000	19,000	16,000		21,500	2700	5000	19,000	16,000	
Outlet	15	35	450	300	240		35	600	1400	370	360	
	% removal						% removal					
Odor ED_{50}	99.9	98.7	91	98.4	98.5	97	99.8	78	72	98.1	98	89
GLC peaks												
1. Dimethyl sulfide	92	87	84	87	89	88	57	68	64	3	37	46
2. Pungent U.P. 90	95	87	98	93	94	93	50	26	21	3	10	22
3. Dimethyl disulfide	92	99.4	99.9	95	91	95	82	96	96	17	39	66
4. Butyric acid	39	56	98.5	94	87	75	70	82	76	84	7	64
5. Propylene sulfide (cabbage 880)	41	93	95	72	88	78	82	95	95	64	92	85
6. Bitter 655	96	97	98	93	-	96	57	39	43	2	-	35
7. Burnt 1233A (pyrazine)	97	92	99.5	92	-	95	34	26	75	4	-	35
8. Burnt 1233B (pyrazine B)	-	75	81	98	-	85	-	82	80	94	-	85
9. Rendering 1335	34	82	91	82	85	75	89	90	94	86	75	87
10. Fatty 1545	62	83	97	81	73	79	89	89	95	79	75	86
11. Burnt 1687 (quinoline)	68	74	98	87	92	84	98	90	96	90	87	93
12. Sulfur 660	-	-	-	-	-	-	-	-	-	-	-	-
13. Cheesy 2002	61	73	94	79	81	78	93	90	94	83	78	88
14. Unpleasant 2582	69	78	96	76	79	79	98	94	96	85	78	90
15. Fatty acid 1980	59	91	97	70	88	81	99	95	95	81	88	92
16. Fatty acid 2160	58	87	98.4	96	98.2	87	90	88	98.9	85	98	92
Average percent removal of each component	69	84	95	86	87	85	78	77	81	57	64	71

* Sample rounds 2 to 6 were collected at the following times: 0.5, 2.5, 8.5, 17.5, and 24 hr, respectively.

deterioration in removal efficiency in the hypochlorite system was evident. An example of this is dimethyl disulfide. Caustic, when fresh, removed 82-96% of dimethyl difulfide, but with time the removal efficiency dropped to 17-39%.

During the experiment, caustic was periodically added to all three stages to maintain a pH above 12. In the sodium hypochlorite stages, maintaining the pH above 12 is critical for optimum odor removal, especially in the final stage of the scrubber. Earlier in this project, an experiment (Test 22) was performed placing the sodium hypochlorite solution that had been used for several hours in the first stage into the last stage. In Test 22, the odor panel found only a 17% reduction in odor removal through the entire three stages, while the chromatograms indicated an average removal of 86%. The results of Test 22 suggested that chlorine was being emitted from the solution. At the time, we were not set up to determine pH and can only hypothesize that the pH had dropped well below 12, resulting in a chlorine odor; however, this last test (Test 32) clearly demonstrates that the sodium hypochlorite solutions are effective over long periods of time as long as the pH is maintained above 12. In Test 32, the pH of the second stage hypochlorite-caustic solution was initially 12.8, and it was 12.2 at 9 hr and 25 hr, with 6 lb of NaOH being added over the duration of the test.

Table A-11 presents the results of blowing fresh air through the scrubber after the 24-hr test. These results show excellent agreement with the previous findings. More material was being emitted from the caustic solution, especially the following compounds:

Pungent U.P. 90
Dimethyl disulfide
Bitter 655
Sulfur 660
Unpleasant 2582

As with the previous test, all tubing was replaced prior to taking the "fresh" air samples. The odor panel found 130 odor units in the outlet from the caustic stage as compared to 30 odor units from the hypochlorite stage. These results indicate that the caustic solution was more saturated with odorous compounds than was the hypochlorite. This is similar to the conclusions from Table 6-5, where the average percent removal of components through the caustic combination was 57 and 64 during the last two samplings compared to an average of 79 removal during the first 3 samplings.

Thus, based upon the parallel scrubbing tests, multiple stages of sodium hypochlorite with excess caustic was found to be the optimum scrubbing combination. Prior to this project, it was believed that using different scrubbing solutions in each stage would be the most efficient method of odor control. The findings from this phase of the project improves the economics of scrubbing systems, because one relatively inexpensive solution can be used in all stages. The use of one scrubbing solution also allows a plant to utilize a counter-current chemical blow-down and make-up scheme, which reduces the chemical costs even further. The continuous blow-down and make-up scheme is described in detail in Section 10.3.

7. EFFECT OF SODIUM HYPOCHLORITE CONCENTRATION ON ODOR REMOVAL

As discussed in the previous chapter, sodium hypochlorite solution at a pH greater than 12 was found to be the most effective scrubbing liquid. In order to properly design the "optimum" scrubbing system, the effect of concentration on odor removal must be established.

In all of the analytical work during this project, hypochlorite concentration was expressed as wt percent equivalent available chlorine (Cl_2) based on the following reaction for producing the sodium hypochlorite (Palin, 1973).

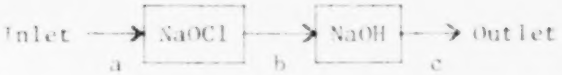
$$Cl_2 + 2NaOH \rightarrow NaOCl + NaCl + H_2O$$

Murthy (1973) studied the effect of reagent concentration on scrubbing efficiency of specific odorous compounds. Murthy used reagent concentrations from 1 to 5 wt%. In general, no measurable difference in removal efficiency was observed by increasing the reagent concentration from 1 to 5%. Based upon Murthy's findings and discussions with chlorine manufacturers, it was postulated that a critical minimum reagent concentration exists, above which a negligible increase in removal efficiency occurs.

During the comparative scrubbing tests, the reagent concentrations were usually near 1 wt% concentration; however, some indication of the effect of concentration can be obtained from the longer test runs in which the chlorine level was allowed to decrease with time. In Test 30, two stages of the laboratory scrubber were used with sodium hypochlorite in the first stage and caustic in the second stage. Samples were collected before and after the first stage to monitor the performance of the sodium hypochlorite stage. The results from Test 30 are presented in Table 7-1. This table indicates that there was no decrease in removal efficiency, even though the chlorine level dropped from 0.81% to 0.65%.

Table 7-1

TEST 30 - SUMMARY



Time (min)	% Cl_2 in 1st Stage	Odor Concentration, ED_{50}			% Removal	
		Inlet (a)	Position (b)	Position (c)	1st Stage	2nd Stage
30	0.81	3,550	---	---	---	---
90	0.78	10,500	590	60	94	90
210	0.65	14,200	465	60	97	87

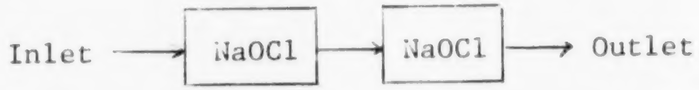
In Test 32, two stages of sodium hypochlorite were operated in series for 25 hours. During the 25 hours, the chlorine level in the first stage decreased 82%, while the chlorine level in the second stage decreased 14%. The odor removal through the two-stage sodium hypochlorite scrubber in test 32 showed no trend with time. The odor removal averaged 84% for the entire test, while the last 2 measurements were 86 and 87%. The results from Test 32, which are summarized in Table 7-2, clearly show the efficiency of the scrubber is not controlled by the chlorine concentration maintained in the scrubbing solutions; at least above some critical minimum concentration.

In order to maintain the reagent concentration above the critical minimum concentration, reagents must be added to the solution, either on a batch or continuous basis. To determine reagent feed rates, it is necessary to obtain data on the chemical consumption rate. Because of the large variation in odor intensity in a rendering plant (a tenfold change in odor level in both the plant ventilating air and in the high-intensity odor stream was observed in samples collected in less than one hour apart), there is also a large variation in the chlorine consumption rate. If the chlorine level is maintained

Table 7-2

TEST 32 - SUMMARY OF RESULTS

Time, hr	% Cl_2 in 1st stage	% Cl_2 in 2nd stage	% removal odor panel ED_{50}	GC average component % removal
0.5	0.93	0.94	99.9	69
2.5	0.88	0.92	98.7	84
8.5	0.71	0.87	91	95
17.5	0.36	0.86	98.4	86
24	0.17	0.81	98.5	87


Inlet
NaOCl
NaOCl
Outlet

at too low a concentration, a high odor level in the scrubber inlet for several hours would deplete the available chlorine. If the chlorine is completely exhausted, drastically reduced odor removal efficiencies can be expected. This may occur at a time when maximum efficiency is required because of the higher than average inlet odor levels. Thus, even though a scrubber will operate efficiently at low chlorine levels, the solutions must be maintained with sufficient chlorine to allow for fluctuations in odor levels.

If the scrubber has multiple stages, a lower chlorine concentration can be maintained in the first stage. If the chlorine level drops to zero in a one-stage scrubber, the resulting drop in efficiency would be drastic. A two-stage system, however, would still have chlorine in the second stage, so that the over-all efficiency would not be reduced as much as with a one-stage system.

The lowest available chlorine level used in the experiments was 0.17%. We do not know how effective a lower chlorine level would be although we suspect that the removal will decrease less than proportional to concentration. However, one should design a plant scrubber for a concentration greater than the minimum, since fluctuations in plant odor load may cause a temporary reduction in actual chlorine concentration in the scrubbing liquor. Further discussion of the design concentrations and the cost of chemicals to achieve given chlorine levels is given in Section 10.3.

8. PERFORMANCE EVALUATION OF THE HORIZONTAL SPRAY SCRUBBER

Alkaline sodium hypochlorite solution was found to be the most effective scrubbing solution. Using the hypochlorite solution, a two-week evaluation of the full-scale horizontal spray scrubber was performed. This evaluation should provide a good indication of the efficiency of spray scrubbers, 30 of which are being used by rendering plants for treating ventilating air.

8.1 Converting to a Continuous Blow-Down, Make-Up System

The current industry practice is to operate the liquid scrubbing tanks on a batch basis. The spent solutions are ordinarily dumped to the sewer every day or two, and fresh scrubbing solutions are prepared. This practice requires considerable labor and also results in the loss of significant quantities of reagents to the sewer, as much as 100 pounds per day as Cl_2. Rapid dumping of the tanks to the sewer can result in excessive pollutant peaks in the sewer. As the batch solutions age, more refractory odorants and partially oxidized odorants can accumulate in the solution, and the scrubber odor removal efficiency can decrease.

The use of the same scrubbing solution in all stages lends itself to a continuous blow-down and make-up system. There are several advantages to the continuous blow-down approach:

- reduced labor cost, because tanks do not have to be emptied and cleaned every day or two
- more consistent scrubber performance. The solutions are kept fresh enough so that scrubber efficiency approaches the maximum.
- reduced chemical costs. In a multiple system, a high degree of chemical utilization is realized; very little is wasted to the sewer in the nearly spent purge stream.

- reduced pollutant surges to the sewer. With the continuous blow-down, a steady 2-4 gpm is sent to the sewer. The load placed on the sewer from this small stream is negligible compared to other plant discharges to the sewer.

Because of the benefits described above, the scrubbing system was modified to a continuous blow-down, make-up system. In designing this system, the objectives were to automatically supply the proper quantities of reagents whenever the scrubber was operating, and to do this without operator intervention. The basic idea was to meter the reagents into the third stage, allow the solution to overflow by gravity to the second stage, and then to the first stage. The overflow from the first stage (blow-down) was directed to the sewer. A diagram of the system is shown in Figure 8-1.

8.2 Control System and Feed Rates

The water system was modified by adding a solenoid valve and rotameter into the water line for the third-stage liquid tank. The solenoid valve was open whenever the scrubber fan was in operation. PVC pipe was used in modifying the water make-up line and for all of the overflow piping.

Chlorine gas was introduced through an eductor, into the third stage liquid pump. Caustic solution was also pumped into the last stage nine minutes out of every hour while the scrubber was operating. The intermittent feeding allowed setting an easily controlled flow rate. This was accomplished by using a 60-minute cycle timer that was activated whenever the scrubber fan was in operation. The timer was wired to a barrel pump which was used to transfer the caustic directly from the 55-gallon drums to the third-stage liquid tank. This avoided any manual handling of caustic solution. Samples from each scrubbing solution tank were collected for pH determination a minimum of twice per day. The intermittent

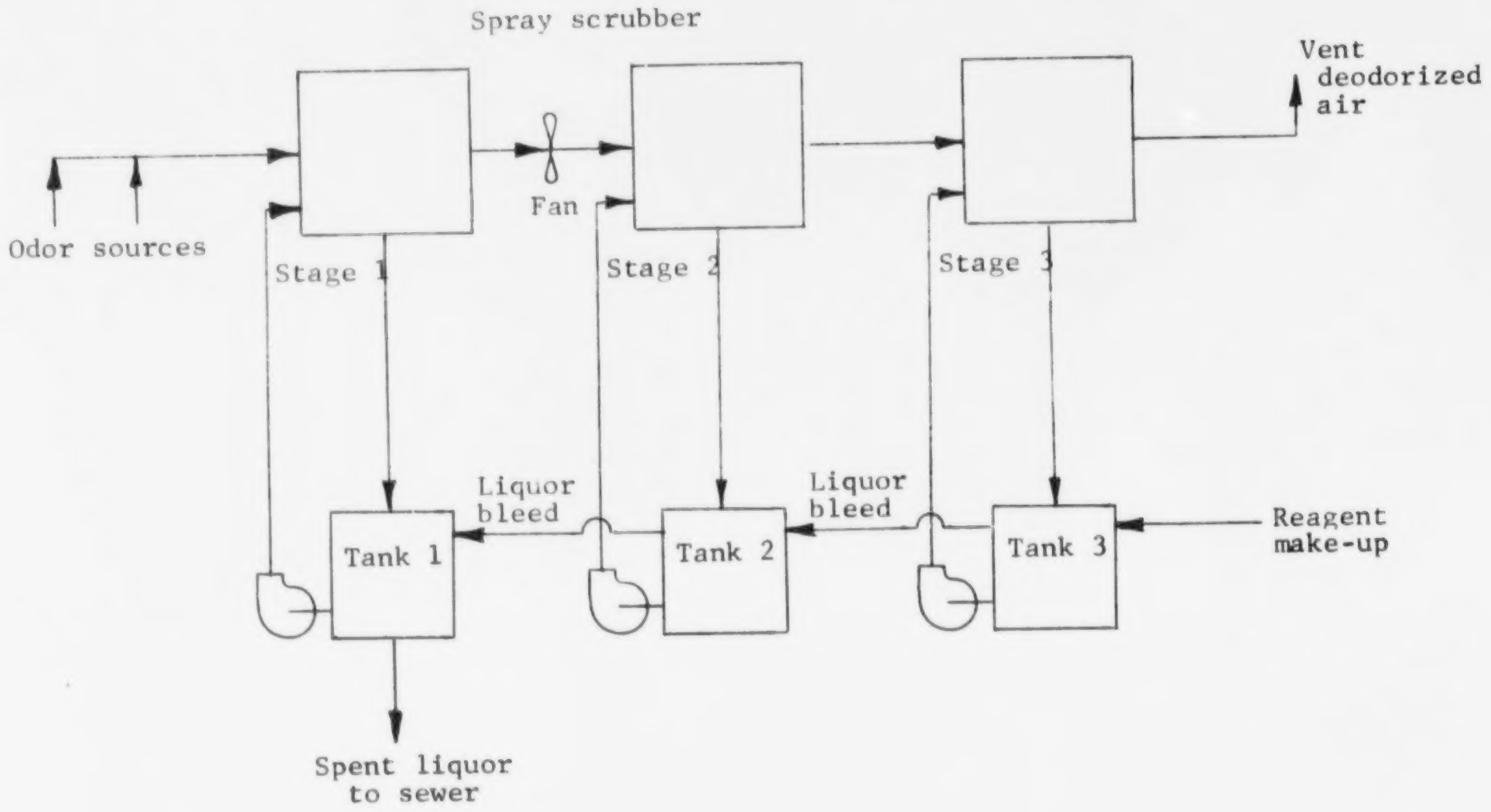

Spray scrubber
Vent deodorized air
Odor sources
Fan
Stage 1
Stage 2
Stage 3
Liquor bleed
Liquor bleed
Tank 1
Tank 2
Tank 3
Reagent make-up
Spent liquor to sewer

Figure 8-1

DIAGRAM OF PLANT SCRUBBER SYSTEM
WITH CONTINUOUS COUNTERCURRENT REAGENT SUPPLY

caustic feeding rate was adjusted to maintain the pH above a target level of 12.

8.3 Description of Plant Test

The plant test was performed from July 8 through July 18. The temperature in Des Moines through the entire two-week period averaged over 90°F, with a range of 70 to 105°F. The horizontal spray scrubber was operated 24 hours a day except for the week-end, when the scrubber was shut down for 46 hours. The continuous cooker was in operation an average of 16-1/2 hours each day during the test period.

The high temperatures resulted in an evaporation loss from the scrubbing solutions that averaged 2.7 gpm, based on the measured make-up water added to the third stage less the blow-down from the first stage. The evaporation rate followed a diurnal pattern, being considerably higher during the afternoon than it was at night. Because of the varying evaporation rate, the blow-down rate varied from less than 0.1 gpm in the afternoons to 4 gpm very early in the morning. The odor levels were the highest during the early morning when the plant processes the "worst" material. Thus, the diurnal pattern was actually advantageous because during the period of highest odor levels, the blow-down was at a maximum rate (4-6 gpm).

Some foaming occurred in all three liquid tanks, although excessive foaming only occurred when the pH was greater than 12.5. The foam in the first stage contained many dead insects and probably a large amount of the organics removed from the air. With the overflow-type blow-down system, the foam was continuously being skimmed off the first stage tank. This prevented large quantities of dead insects from accumulating in the first stage.

It was also found necessary to drain 10 to 20 gallons off the bottom of the first tank each day because of the heavier particulates that were settling on the bottom of the tank. As a routine procedure, 10-20 gallons were drained off the bottom of each tank each day, although the first tank contained by far the most sediment. Routine draining of 10-20 gallons should extend the operating periods between cleaning of the nozzles.

The chlorine concentration in each tank was measured several times each day by titration. After the first two days of operating, a 14 lb/hr chlorine rotameter was installed in the chlorine make-up line because the original 8 lb/hr rotameter was too small. The chlorine concentrations in each tank throughout the two-week test are presented in Chapter 10, Figure 10-3. Most of the chlorine demand occurs in the first stage of the scrubber where the greatest quantity of odorous compounds are removed. The large chlorine demand in the first stage is evident from Figure 10-3, where there is very little difference in the chlorine concentration between tanks 2 and 3, but there is a large drop in the chlorine level from tank 2 to tank 1. Also from Figure 10-3, a large fluctuation in the chlorine level in tanks 2 and 3 is evident. This is caused by the varying odor loading on the scrubber and the varying blowdown rate.

The pH in the first tank remained between pH 9 and 10 throughout the entire test. The pH in tank 3 varied from pH 9.5 to 12.5; however, throughout most of the test the pH in tank 3 remained between pH 11 and 12 which was lower than the target value of pH 12. This was due to the malfunctioning of a pH meter that was brought to the plant.

In order to check the build-up in alkalinity, pH titrations were performed six times on each solution. During the first two days there was an increase in the alkalinity of each solution; however, after the first two days no further increases were observed, indicating that the rate of accumulation of material was equal to the loss of material in the blow-down.

Thus, steady conditions were achieved in the continuous blow-down and make-up system.

8.4 Results of the Performance Test

This test using the continuous blow-down system was very successful. The odor removal results are presented in Tables 8-2 through 8-7 and are summarized in Table 8-1. The system operated for over 175 hours and no performance deterioration was observed with time. Throughout the entire test the outlet odor level averaged 57 odor units, a level that is very satisfactory for most rendering plants.

The plant ventilating air entering the scrubber contained odor levels from 165 to 2,500 odor units. The outlet from the scrubber contained from 20 to 135 odor units through the test period. For sample round #7 at 175 hours, the odor panel found 165 odor units in the inlet and 100 odor units in the outlet. The pH in the last stage had dropped to pH 9.5 when the samples were taken. According to the gas chromatograms, a high level of removal of the compounds occurred. Thus, it appears that chlorine contributed a large part of the outlet odor level measured by the odor panel. During all the other samplings, the pH in the last stage was above pH 10, and usually above pH 11. This result emphasizes the importance of the high pH in the final stage of the scrubber system.

The average removal of each component for the entire test was 85% (standard deviation of 11%) according to the chromatograph, while the odor level reduction averaged 92% (standard deviation of 3%) excluding the last sampling. Throughout the entire two-week test, no odor complaints were received by the rendering plant from the surrounding community. The extremely hot July temperatures and the heavy load of rancid, dead animals processed by the plant should produce the most severe conditions that rendering plants must operate under. The sodium hypochlorite scurbbing solution with the continuous blow-down system was

Table 8-1

SUMMARY OF SCRUBBING TEST 34
PLANT SCRUBBER

Sample No.	1	2	3	4	5	6	7	Average
Time	29 hr	31 hr	77 hr	84 hr	125 hr	150 hr	175 hr	
Inlet odor, ED_{50}	2500	380	180	190	550	-	165	
Outlet odor, ED_{50}	135	25	20	20	40		100	57
	% Removal							
Odor ED_{50}	95	93	89	89	93	-	(39)	92(83)
GLC peaks								
1. Dimethyl sulfide	-	49	58	87	-	99.3	97	78
2. Pungent U.P. 90	-	-	-	-	-	-	-	-
3. Dimethyl disulfide	-	-	-	-	-	-	-	-
4. Butyric acid	93	-	99	94	-	94	71	90
5. Propylene sulfide (cabbage 880)	83	40	99	88	-	82	83	79
6. Bitter 655	-	-	-	-	-	-	-	-
7. Burnt 1233A (pyrazine)	94	81	90	61	-	88	83	83
8. Burnt 1233B (pyrazine B)	99.1	50	99	85	-	93	99	88
9. Rendering 1335	99	-	89	97	-	95	83	93
10. Fatty 1545	97	53	85	97	-	75	99.8	84
11. Burnt 1687 (quinoline)	97	89	86	87	-	90	75	87
12. Sulfur 660	-	-	-	-	-	-	-	-
13. Cheesy 2002	97	67	92	97	-	90	86	88
14. Unpleasant 2582	98	-	79	82	-	72	82	83
15. Fatty acid 1980	79	-	93	78	-	52	-	76
16. Fatty acid 2160	91	-	93	96	-	-	-	93
Average removal of each component	93	61	88	87	-	85	86	85

PH LEVELS								
1st Stage	9-10	9-10	9-10	9-10	9.3	9.1	9.4
2nd Stage	9-10	9-10	> 10	> 10	9.3	9.4	9.5
3rd Stage	> 10	> 10	> 10	> 10	10.9	11.2	9.5

Table 8-2

RESULTS OF SCRUBBING TEST 34
PLANT SCRUBBER, TIME: 29 HOURS

	Inlet	Outlet	% Removal
Odor ED_{50}	2500	135	95
GLC peaks, μg/liter air			
1. Dimethyl sulfide	-	-	-
2. Pungent U.P. 90	-	-	-
3. Dimethyl disulfide	-	-	-
4. Butyric acid	0.75	0.05	93
5. Propylene sulfide (cabbage 880)	0.47	0.08	83
6. Bitter 655	-	-	-
7. Burnt 1233A (pyrazine)	2.07	0.13	94
8. Burnt 1233B (pyrazine B)	6.52	0.06	99.1
9. Rendering 1335	266.2	3.10	98.8
10. Fatty 1545	15.41	0.50	97
11. Burnt 1687 (quinoline)	9.31	0.30	97
12. Sulfur 660	-	-	-
13. Cheese 2002	9.48	0.32	97
14. Unpleasant 2582	4.48	0.11	98
15. Fatty acid 1980	5.22	1.09	79
16. Fatty acid 2160	4.43	0.39	91
Average percent removal of each component			93

Table 8-3

RESULTS OF SCRUBBING TEST 34
PLANT SCRUBBER, TIME: 31 HOURS

	Inlet	Outlet	% Removal
Odor ED_{50}	380	25	93
GLC peaks, μg/liter air			
1. Dimethyl sulfide	0.92	0.47	49
2. Pungent U.P. 90	-	-	-
3. Dimethyl disulfide	-	-	-
4. Butyric acid	-	-	-
5. Propylene sulfide (cabbage 880)	0.10	0.06	40
6. Bitter 655	-	-	-
7. Burnt 1233A (pyrazine)	0.16	0.03	81
8. Burnt 1233B (pyrazine B)	0.34	0.17	50
9. Rendering 1335	-	-	-
10. Fatty 1545	0.45	0.21	53
11. Burnt 1687 (quinoline)	0.87	0.10	89
12. Sulfur 660	-	-	-
13. Cheesy 2002	0.21	0.07	67
14. Unpleasant 2582	-	-	-
15. Fatty acid 1980	-	-	-
16. Fatty acid 2160	-	-	-
Average percent removal of each component			61

Table 8-4

RESULTS OF SCRUBBING TEST 34
PLANT SCRUBBER, TIME: 77 HOURS

	Inlet	After first stage	Outlet	Total % Removal
Odor ED_{50}	180	65	20	89
GLC peaks, μg/liter air				
1. Dimethyl sulfide	0.76	0.07	0.32	58
2. Pungent U.P. 90	-	-	-	-
3. Dimethyl disulfide	-	-	-	-
4. Butyric acid	0.30	0.09	< 0.01	99
5. Propylene sulfide (cabbage 880)	0.14	0.07	< 0.01	99
6. Bitter 655	-	-	-	-
7. Burnt 1233A (pyrazine)	0.06	0.04	< 0.01	90
8. Burnt 1233B (pyrazine B)	0.64	0.26	< 0.01	99
9. Rendering 1335	24.05	8.27	2.54	89
10. Fatty 1545	2.21	0.82	0.34	85
11. Burnt 1687 (quinoline)	0.72	0.30	0.10	86
12. Sulfur 660	-	-	-	-
13. Cheesy 2002	1.26	0.79	0.10	92
14. Unpleasant 2582	0.34	0.48	0.07	79
15. Fatty acid 1980	1.07	0.77	0.07	93
16. Fatty acid 2160	1.30	1.25	0.09	93
Average percent removal of each component				88

Table 8-5

RESULTS OF SCRUBBING TEST 34
PLANT SCRUBBER, TIME: 84 HOURS

	Inlet	Outlet	% Removal
Odor ED_{50}	190	20	89
GLC peaks, μg/liter air			
1. Dimethyl sulfide	1.07	0.14	87
2. Pungent B.P. 90	-	-	-
3. Dimethyl disulfide	-	-	-
4. Butyric acid	0.70	0.04	94
5. Propylene sulfide (cabbage 880)	0.92	0.11	88
6. Bitter 655	-	-	-
7. Burnt 1233A (pyrazine)	0.18	0.07	61
8. Burnt 1233B (pyrazine B)	1.06	0.16	85
9. Rendering 1335	70.60	1.85	97
10. Fatty 1545	7.08	0.21	97
11. Burnt 1687 (quinoline)	3.38	0.45	87
12. Sulfur 660	-	-	-
13. Cheese 2002	5.06	0.13	97
14. Unpleasant 2582	1.81	0.32	82
15. Fatty acid 1980	0.64	0.14	78
16. Fatty acid 2160	2.48	0.09	96
Average percent removal of each component			87

Table 8-6

RESULTS OF SCRUBBING TEST 34
PLANT SCRUBBER, TIME: 150 HOURS

	Inlet	Outlet	% Removal
Odor ED$_{50}$	-	-	-
GLC peaks, ng/liter air			
1. Dimethyl sulfide	7.42	0.05	99.3
2. Pungent U.P. 90	-	-	-
3. Dimethyl disulfide	-	-	-
4. Butyric acid	1.25	0.07	94
5. Propylene sulfide (cabbage 880)	0.34	0.06	82
6. Bitter 655	-	-	-
7. Burnt 1233A (pyrazine)	0.33	0.04	88
8. Burnt 1233B (pyrazine B)	3.35	0.23	93
9. Rendering 1335	79.81	4.27	95
10. Fatty 1545	9.00	2.24	75
11. Burnt 1687 (quinoline)	1.76	0.18	90
12. Sulfur 660	-	-	-
13. Cheesy 2002	2.41	0.25	90
14. Unpleasant 2582	1.30	0.37	72
15. Fatty acid 1980	1.94	0.94	52
16. Fatty acid 2160	-	-	-
Average percent removal of each component			85

Table 8-7

RESULTS OF SCRUBBING TEST 34
PLANT SCRUBBER, TIME: 175 HOURS

	Inlet	Outlet	% Removal
Odor ED$_{50}$	165	100	39
GLC peaks, ng/liter air			
1. Dimethyl sulfide	7.22	0.20	97
2. Pungent U.P. 90	-	-	-
3. Dimethyl disulfide	-	-	-
4. Butyric acid	0.24	0.07	71
5. Propylene sulfide (cabbage 880)	0.23	0.04	83
6. Bitter 655	-	-	-
7. Burnt 1233A (pyrazine)	0.12	0.02	83
8. Burnt 1233B (pyrazine B)	0.93	<0.01	99
9. Rendering 1335	35.08	5.86	83
10. Fatty 1545	5.86	<0.01	99.8
11. Burnt 1687 (quinoline)	1.46	0.36	75
12. Sulfur 660	-	-	-
13. Cheesy 2002	2.10	0.29	86
14. Unpleasant 2582	0.34	0.06	82
15. Fatty acid 1980	-	-	-
16. Fatty acid 2160	-	-	-
Average percent removal of each component			86

extremely successful in maintaining an acceptable quality scrubber discharge (less than 150 odor units) for the entire two-week test. This two-week test clearly demonstrated the effectiveness of the continuous blow-down system in maintaining fresh solutions and good odor reductions.

9. PERFORMANCE EVALUATION OF PACKED-BED SCRUBBERS

An additional objective of this program was to evaluate the performance of packed-bed scrubbers treating the high odor intensity air streams, typically 5,000 to 50,000 odor units. Evaluating the performance of a scrubber system requires a determination of empirical operating characteristics of the scrubbing unit and the liquid solution, guided by theoretical analysis. In this section, the performance of the scrubbing solutions, the mass transfer characteristics of odor removal, and other design features of packed-bed scrubbers will be discussed.

9.1 Summary of Comparative Tests

The laboratory scrubber installed at the Des Moines rendering plant was used to evaluate the odor removal of packed-bed scrubbers. Comparative scrubbing tests, which were described in Chapter 6, were utilized to determine the optimum combination of scrubbing solutions.

According to the test results, using a single scrubbing reagent, sodium hypochlorite, in all stages provided the highest degree of odor reduction for both low- and high-intensity odors. Three separate evaluations of this scrubbing reagent were performed during the initial test work, and the results are summarized below.

	Odor Level (ED$_{50}$)			GLC
	Inlet	Outlet	% Removal	Average % Removal of Each Component
Test 11	63,000	550	99.1	--
Test 25	8,300	20	99.8	--
Test 26	--	--	--	95

Based upon the outstanding results shown above, further tests were performed to directly compare the hypochlorite combination with other promising combinations. These results, which are also described in detail in Chapter 6, are summarized below.

	Length of Test, hr	Average Odor Levels (ED_{50})			GLC
		Inlet	Outlet	Average % Removal	Average % Removal of Each Component
Test 31	10	5,600	38	96	83
Test 32	24	12,800	208	97	85

These results were obtained with a two-stage packed scrubber, as compared to a three-stage scrubber used in the previous tests. Even after the solutions had been subjected to the high intensity odors for 24 hours in Test 32, the scrubbing solutions were still very effective. The pH was maintained above 12 throughout Test 32, and this was considered an important factor in achieving these high removals. Throughout Test 32, the pH in both stages was maintained above pH 12 by adding caustic.

As discussed in Chapter 6, maintaining the pH above 12 was found to be essential based on the results of Tests 22 and 32. In Test 22, the pH was not maintained and the odor panel found only a 17% reduction in the odor level. The chromatograms in Test 22 indicated an average removal of 86%, suggesting that a major part of the odor smelled by the panel was chlorine or the reaction products between the chlorine and the odorous compounds. In Test 32, the pH was maintained above pH 12 for a 24-hr test, and no deterioration in removal was reported. The difference in these two tests emphasizes the importance of maintaining a pH of 12 to achieve odor removals greater than 90%.

9.2 Mass Transfer as a Function of Packing Depth

In designing a packed-bed scrubber, the two most important parameters that must be specified are the gas flow-rate to be treated and the desired removal efficiency. The removal efficiency in gas-liquid absorbing systems is often written in terms of mass transfer units, where

$$NTUG = \ln\left(\frac{YO}{YE}\right)$$

where

NTUG is number of mass transfer units

YO is inlet odor level

YE is outlet odor level

To obtain a greater reduction in odor, the scrubber must provide more mass transfer units, (assuming that the increase does not have an effect on any chemical reactions occurring). Mass transfer theory for absorbing pure compounds from the gas to the liquid phase states that if the packing depth doubles, the number of mass transfer units also doubles, as long as the liquid and gas flow rates are held constant. To ascertain if the mass transfer theory is valid for odor removal, the height of the packing in the laboratory scrubber was increased from 2 to 4 feet. The number of mass transfer units for Test 33 with the taller columns are compared below with the mass transfer units for the shorter columns (Tests 31 and 32) under similar operating conditions, using sodium hypochlorite with the pH greater than 12.

Test No.	No. of Stages	Height of packing per stage Ft	Odor units		Average NTUG per stage[1]
			YO	YE	
31 & 32	2	2	10,000	140	2.13
33	1	4	9,650	277	4.12

These data suggest that doubling the column height effectively doubles the number of mass transfer units, NTUG. This result is in agreement with mass transfer theory.

Another method of increasing the number of mass transfer units involves a reduction of the gas flow rate. If a smaller volume of gas is being treated, the contact time between the gas and the liquid increases, resulting in a higher removal. Using just one 4-ft stage of the scrubber, the gas flow rate was reduced from the normal 17 cfm to 11.7 cfm. This experiment was performed twice, and the following results were obtained using just the one stage.

	Gas Flow (cfm)	Odor Level		
		Inlet	Outlet	% Removal
Test 33a	11.7	15,000	20	99.9
Test 33b	11.7	4,300	60	98.6

The results indicate that odor removals greater than 98% can be achieved in a single-stage packed scrubber. This conclusion is based on a limited number of tests, and should be repeated for confirmation. If confirmed, it would show that the selection of a single- or multi-stage scrubber system is one of economics. The determination of the economic optimum number of stages is discussed in Chapter 10, based on a mass transfer model.

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[1] Average NTUG = $\dfrac{\sum_{i=1}^{n} (\text{NTUG})_i}{n}$ where n = total number of samplings

See Appendix 6 for method of calculation.

9.3 Laboratory Scrubber Liquor Life Test

Tests using the three-stage packed-bed scrubber resulted in odor removals greater than 99%, as shown in Table 6-3. However, only Tests 31 and 32 were performed for an adequate period of time to provide an estimate of the life of the scrubbing solutions. Both of these earlier tests were performed utilizing batch scrubbing solutions. Additional data were needed using the continuous blow-down scheme to determine reagent consumption rates.

Using the high strength cooker off-gas, a five-day test was undertaken to achieve the following objectives:

- demonstrate that packed bed scrubbers could successfully deodorize high-strength gases from a rendering plant
- establish the chemical make-up and blow-down rates for treating high-strength gases.

The following tests suggest that when treating incinerator inlet air, the blow-down rate is controlled by a different mechanism than when treating plant ventilating air. For plant ventilating air, the blow-down rate should be set to maintain a chlorine residual in the first stage. For incinerator inlet air, the blow-down rate should be set to purge the solutions of odorous refractory compounds, which would otherwise accumulate. Although the concentrations of these compounds are not known, the objective should be to find a blow-down rate that will prevent any evidence of their effect on the odor removal of the scrubber.

9.3.1 Test Procedure

Three 6-ft glass columns were installed, each with 4 ft of packing to provide a large number of mass transfer units. The continuous blow-down and make-up system was simulated by manually transferring a portion of the solution from tank to tank every hour. The process was similar to the horizontal spray scrubber continuous blow-down system shown in Figure 8-1.

Since all previous work had been performed using batch scrubber solutions, the necessary blow-down rate and chemical make-up requirements were estimated and adjusted throughout the duration of the test, as explained below.

At the start of Test 35, the following conditions were measured.

	NaOCl (as Cl_2) wt %	pH
Tank #1	0.25	11.8
Tank #2	0.5	12.1
Tank #3	0.75	12.4

After 10 hours of operation, the following concentrations were measured in each tank.

	NaOCl (as Cl_2) wt %	pH
Tank #1	0.02	9.5
Tank #2	0.45	9.7
Tank #3	0.74	10.7

At the end of 10 hours, the make-up water and caustic addition rates were increased. Because of the pH meter malfunction described in the previous chapter, analysis of pH had to be performed at IITRI during the following week. Thus, proper control of caustic addition was not achieved during the test run. At the end of the 23rd hour of operation, a residual rancid chlorine odor in all of the scrubbing solutions was very noticeable (the odor panelists also noted a chlorine-like odor in the outlet bag samples), so the water make-up rate was increased from 1.5 gal/hr to 2.0 gal/hr and the caustic increased from 0.1 lb/hr to 0.14 lb/hr. Throughout the remainder of the test, the following conditions prevailed.

	NaOCl (as Cl_2) %	pH
Tank #1	0.10-0.14	9.3- 9.6
Tank #2	0.35-0.42	9.5- 9.8
Tank #3	0.40-0.45	9.9-10.6

The pH was still not maintained above pH 12 in the last stage even when the dosage rate was increased. It was also observed that the residual odor in all of the tank solutions persisted for the remainder of the test, even with the increase in the water make-up rate; however, no residual odor was evident in the scrubbing solutions used during the full-scale plant test for plant ventilating air described in Chapter 8. These observations, and GLC data given below support the earlier statement that the mechanism that controls the blow-down rate varies depending upon the strength of the odor.

9.3.2 Laboratory Scrubber Test Results

The results of the laboratory scrubber liquor-life test (Test 35) are presented in Tables 9-2 through 9-5 and are summarized in Table 9-1. The gas chromatograph results show an average removal of each component for the entire test of 88%. The removal was expected to be considerably greater than 88% based on the previous batch tests, #31 and 32. In Tests 31 and 32, which were performed utilizing only two stages of 2-ft packing, the odorous compounds were reduced an average of 83% and 85% respectively. In this liquor life test, taller columns

Table 9-1

SUMMARY OF SCRUBBING TEST 35
LABORATORY SCRUBBER

Sample round time, hrs.		1 9 hours	2 14 hours	3 22 hours	4 32 hours	5 48 hours	Average
	inlet	1800 *	2750	1700	4800	35,500	
	outlet	6200	1120	1150	95	7,600	
		% removals					
Odor ED_{50}			59	32	98	79	67
GLC peaks							
1. Dimethyl sulfide		98.2	-	-	94	91	94
2. Pungent U.P. 90		95	-	-	54	90	80
3. Dimethyl disulfide		99.6	-	99.9	99.9	92	98
4. Butyric acid		-	-	98.9	99	-	99
5. Propylene sulfide (cabbage 880)		97	-	98.9	99	-	98
6. Bitter 655		99.9	-	55	47	32	58
7. Burnt 1233A (pyrazine)		87	-	99	-	-	93
8. Burnt 1233B (pyrazine B)		98.4	-	99	74	-	90
9. Rendering 1335		36	-	97	98.4	-	77
10. Fatty 1545		67	-	98	98	-	88
11. Burnt 1687 (quinoline)		28	-	96	99.7	-	75
12. Sulfur 660		-	-	-	-	-	-
13. Cheesy 2002		-	-	95	98.2	-	97
14. Unpleasant 2582		73	-	95	96	-	88
15. Fatty acid 1980		75	-	95	98.7	-	90
16. Fatty acid 2160		-	-	92	99.6	-	96
Average percent removal of each component		74	-	94	90	76	88

* Either these measurements were in error, or the samples were mislabeled

Table 9-2

RESULTS OF SCRUBBING TEST 35-1
LABORATORY SCRUBBER, TIME: 9 HOURS

	Inlet	Outlet	% removal
Odor ED_{50}	1800	6200	-
GLC peaks, μg/liter air			
1. Dimethyl sulfide	21.60	0.39	98.2
2. Pungent U.P. 90	1.68	0.08	95
3. Dimethyl disulfide	2.68	<0.01	99.6
4. Butyric acid	-	-	-
5. Propylene sulfide (cabbage 880)	1.64	0.05	97
6. Bitter 655	48.24	<0.01	99.9
7. Burnt 1233A (pyrazine)	1.17	0.15	87
8. Burnt 1233B (pyrazine B)	9.28	0.15	98.4
9. Rendering 1335	21.08	13.46	36
10. Fatty 1545	2.37	0.78	67
11. Burnt 1687 (quinoline)	1.13	0.81	28
12. Sulfur 660	-	-	-
13. Cheesy 2002	0.42	-	-
14. Unpleasant 2582	1.31	0.36	73
15. Fatty acid 1980	2.72	0.68	75
16. Fatty acid 2160	-	1.19	-
Average percent removal of each component			74

Make-up Rates

Water 4.5 liters per hour
Caustic 42 gms per hour (as NaOH)
Chlorine 52 gms per hour (as Cl_2)

Table 9-3

RESULTS OF SCRUBBING TEST 35-3
LABORATORY SCRUBBER, TIME; 22 HOURS

	Inlet	Outlet	% removal
Odor ED_{50}	1700	1150	29
GLC peaks, μg/liter air			
1. Dimethyl sulfide	-	-	-
2. Pungent U.P. 90	-	-	-
3. Dimethyl disulfide	15.36	<0.01	99.9
4. Butyric acid	1.85	0.02	98.9
5. Propylene sulfide (cabbage 880)	3.54	0.04	98.9
6. Bitter 655	52.66	23.78	55
7. Burnt 1233A (pyrazine)	0.27	<0.01	99
8. Burnt 1233B (pyrazine B)	1.27	<0.01	99
9. Rendering 1335	207.7	5.79	97
10. Fatty 1545	26.13	0.64	98
11. Burnt 1687 (quinoline)	6.68	0.26	96
12. Sulfur 660	-	-	-
13. Cheesy 2002	6.78	0.34	95
14. Unpleasant 2582	4.08	0.19	95
15. Fatty acid 1980	11.21	0.60	95
16. Fatty acid 2160	12.90	0.98	92
Average percent removal of each component			94

Make-up Rates

Water 5.7 liters per hour
Caustic 52 gms per hour (as NaOH)
Chlorine 52 gms per hour (as Cl_2)

Table 9-4

RESULTS OF SCRUBBING TEST 35-4
LABORATORY SCRUBBER, TIME: 32 HOURS

	Inlet	Outlet	% removal
Odor ED_{50}	4800	95	98
GLC peaks, μg/liter air			
1. Dimethyl sulfide	22.10	1.42	94
2. Pungent U.P. 90	15.37	7.06	54
3. Dimethyl disulfide	7.38	<0.01	99.9
4. Butyric acid	0.83	<0.01	99
5. Propylene sulfide (cabbage 880)	1.11	<0.01	99
6. Bitter 655	36.99	19.50	47
7. Burnt 1233A (pyrazine)	-	-	-
8. Burnt 1233B (pyrazine B)	1.54	0.40	74
9. Rendering 1335	80.01	1.30	98.4
10. Fatty 1545	9.84	0.22	98
11. Burnt 1687 (quinoline)	2.86	0.01	99.7
12. Sulfur 660	-	-	-
13. Cheesy 2002	2.78	0.05	98.2
14. Unpleasant 2582	1.09	0.04	96
15. Fatty acid 1980	4.67	0.06	98.7
16. Fatty acid 2160	5.09	0.02	99.6
Average percent removal of each component			90

Make-up Rates

Water 7.6 liters per hour
Caustic 70 gms per hour (as NaOH)
Chlorine 52 gms per hour (as Cl_2)

Table 9-5

RESULTS OF SCRUBBING TEST 35-5
LABORATORY SCRUBBER, TIME: 48 HOURS

	Inlet	Outlet	% removal
Odor ED_{50}	35,500	7600	79
GC peaks, μg/liter air			
1. Dimethyl sulfide	12.03	1.10	91
2. Pungent U.P. 90	22.15	2.19	90
3. Dimethyl disulfide	10.62	0.82	92
4. Butyric acid	-	-	-
5. Propylene sulfide (cabbage 830)	-	-	-
6. Bitter 655	50.47	34.14	32
7. Burnt 1233A (pyrazine)	-	-	-
8. Burnt 1233B (pyrazine B)	-	-	-
9. Rendering 1335	-	-	-
10. Fatty 1545	-	-	-
11. Burnt 1687 (quinoline)	-	-	-
12. Sulfur 660	-	-	-
13. Cheesy 2002	-	-	-
14. Unpleasant 2582	-	-	-
15. Fatty acid 1980	-	-	-
16. Fatty acid 2160	-	-	-
Average percent removal of each component			76

Makeup Rates

Water 7.0 liters per hour
Caustic 30 gms per hour (as NaOH)
Chlorine [illegible] gms per hour (as Cl

were utilized with 4 ft of packing. Table 9-1 shows that the removal efficiency for Bitter 655 as well as for several other odorous compounds decreased throughout the entire test. (For Bitter 655, the removal decreased from an initial 99.9% to a final removal of 32%.) This indicates that the blow-down rate was indeed too low, which resulted in the accumulation of certain compounds in the solution. The limited removal of specific compounds suggests that either the compounds accumulated more rapidly than the oxidation rate, or that sodium hypochlorite was not oxidizing these compounds at all.

The odor panel reported low removals (67% average, excluding sample 35-1) and also reported a strong smell of chlorine in all of the outlet bag samples. Both the chlorine smell and poor odor level reductions can be attributed to the occurrence of a low pH (9.9-10.7) in the last stage. When the caustic and the blow-down rates were increased after 23 hours of operation, there was an improvement in the performance. The odor panel found that the outlet odor levels were lower (98% and 79% removal) for samples taken after this change.

9.3.3 Discussion

Because of the unexpected different scrubbing behavior of incinerator inlet air compared with plant ventilating air, insufficient data were collected to conclusively determine the optimum scrubbing reagent concentrations and purge rates for high intensity odors. Therefore, the estimates for reagent costs for incinerator inlet are not as clearly defined. The complex nature of odors results in a very large number of control variables (i.e., make-up rates, reagent concentrations, liquid mass flux, gas mass flux). Additional field work is still needed before a clear understanding of high intensity odor removal can be obtained.

Although this test did not demonstrate that odor removal above 90% and preferably 99% could be sustained using a continuous blow-down system, a great deal of design information was obtained. It is clear now that the initial blow-down and caustic rates were too low and the system never fully recovered from the initial settings. However, the performance of the system was improving after the blow-down and caustic rates were adjusted, which suggests that higher rates should be further investigated.

The earlier comparative tests (#31 and #32) demonstrated that removals of 97% could be sustained even in a batch system for considerable lengths of time. The comparison below shows the different results obtained.

Test 32	Test 35
• Two stages, 2 ft of packing, batch test	• three stages, 4 ft of packing, continuous blow-down and make-up
• 24-hr test, GC removal averaged 85%. Odor panel reported 97% removal.	• GC results averaged 88% removal. Odor panel reported 67% removal
• pH maintained above pH 12	• pH level below pH 11 throughout most of the test

The difference in efficiency between Test 32 and Test 35 must be attributed to the difference in the pH levels maintained.

Temperature is one other factor that could have affected the performance of the scrubbing liquids. In previous tests, the gas and liquid temperatures were measured in the range of 55 to 70°F. In Test 35, the temperatures of gas and liquid were measured at 90 to 100°F, as a result of the warmer ambient temperature at the time. The effect of temperature is to change the solubility at a given vapor pressure of the odorant compounds; for example, increasing the temperature from 50 to 86°F reduces the amount of ammonia that water can absorb by over 50% (Treybal, 1967, p. 221). The effect of temperature on the scrubbing results cannot be deduced from the data because the pH also varied at the same time. In any future work, the possible effect of temperature should be further considered.

9.4 Conclusions

The objective of the week-long Test 35 was to verify the performance of packed-bed scrubbers to treat high odor intensity (5,000 to 50,000 odor units) process air streams. The test did not successfully demonstrate the design. Instead, it showed that we have not yet found the optimum values of pH, reagent concentration, and purge rate in scrubbing of high-intensity odors. The importance of maintaining the pH above 12 in the last stage was clearly demonstrated, and increasing the purge rate above 1 gal/hr for 20 cfm air flow was also indicated.

The scrubber design, which this test was intended to verify, was based on the idea that removal of odorous compounds by packed-bed scrubbers follows the same mass transfer principles as scrubbing of pure compounds, provided that conditions can be found such that chemical reaction rates do not limit the scrubbing process. The necessary mass transfer data was obtained, as discussed in Chapter 10, and includes the effect of gas and liquid flux on the mass transfer coefficient. We still feel that a scrubber designed on these mass-transfer principles will perform as expected, but experimental verification requires further measurements to determine the optimum values of pH, reagent concentration, and purge rates in scrubbing of high-intensity odors.

10. DESIGN AND COST OF COUNTERCURRENT PACKED TOWER GAS SCRUBBING SYSTEM

A computerized design procedure for packed towers was developed in a previous project (Report No. EPA-R2-72-088). This scrubber design and cost model has been updated based on the data collected from the present project. When the odor reduction desired and the number of stages are specified, the computer model will determine the least cost design. A description of the model and examples of utilization are provided within this report.

10.1 Input Data

The following list itemizes and describes the required input data for use of the design model.

1. Type of Packing

   The size and type of packing must be specified. All of the work to date has been with Intalox saddles, although the program is capable of handling many types of packing.

2. Type of material of construction to be used for the tower.

   Any material can be specified. Fiberglass-reinforced plastic has been used for all of the design calculations because it is available for commercially-built scrubbers and is corrosion-resistant for the recommended scrubbing liquids.

3. Cost Index (CI)

   To keep the program current, all cost data that were collected was converted to 1957-59 costs. By utilizing the Chemical Engineering Plant Cost Index (1957-59 = 1.00) (published in *Chemical Engineering*) only one factor must be adjusted to formulate the present cost of the installed equipment.

   All cost estimates in this report are based on a cost index of 1.75, which is the projected index for December 1974.

4. Material Cost Factor (MCF)

Depending upon the type of material of construction specified in Item 2, a material cost factor must be determined. The cost equations in the model use as a basis carbon steel = 1.0. Thus, the relative fabricated cost of the material specified as compared to carbon steel must be determined. For stainless steel, MCF = 2.25 (Popper, 1970) and for fiberglass, MCF = 1.50 (Graham, 1971; Process Equipment Corp., 1974).

5. Maximum Liquid Flux (LMAX)

The maximum liquid rate ($lb/hr\text{-}ft^2$) must be supplied. LMAX is a function of the type and size of packing used. For 1-1/2-in. Intalox Saddles, LMAX = 40,000 $lb/hr\text{-}ft^2$.

6. Henry's Law Constant (HENRY)

Henry's law constant is defined as the partial pressure of the gas divided by the mole fraction of the solute in the liquid at equilibrium. For compounds that are very soluble in the liquid, the mole fraction in the solute is much greater than the partial pressure at low gas concentrations; thus, Henry's law constant approaches zero. For odor control, HENRY can be taken equal to zero.

7. Efficiency of the Pumps (EP)

This is used to calculate the pump horsepower. An EPA = 0.5 was used throughout the entire study.

8. Efficiency of the Fan (EF)

The fan efficiency was used to calculate the fan horsepower requirements. A value of 0.55 was chosen for the design model.

9. Operating Hours (HRS)

HRS is the number of hours the scrubber operates per year. A value of 4,000 hours was selected. This is equivalent to two shifts per day, five days per week.

10. Temperature (T) °F

The temperature of the gas must be specified. In the examples provided, the temperature was set at 70°F.

11. Cost of Electricity (CE)

A value of $0.025/KWH was assigned, based on 1974 industrial electricity rates of Commonwealth Edison in Chicago.

12. Cost Factor for Maintenance (CM)

CM is a constant used to calculate the annual maintenance cost. A value of 8 for CM was used in this study.

13. Amortization Factor (AMF)

This is based on the estimated useful life of the scrubber. The useful life was projected to be 15 years at 10% interest on the capital investment, or 13% per year.

14. Porosity of the Packing (ϵ)

Porosity is the void space of a cubic foot of packing. This is a function of the type and size of packing, and data are available from manufacturers.

15. Surface Area of the Packing (Ap) ft^2/ft^3

This is also a function of the type and size of packing specified.

16. Equivalent Diameter of a Particle Packing (DS) ft

This is also a function of the type and size of packing.

17. Constants Used for Computing the Pressure Drop (Alpha)(Beta)

A function of the type and size of packing.

18. Installed Cost of Packing (CPA) $/ft^3$

19. Number of Stages in the Scrubber (NS)

20. Ratio of the Mass Transfer Rate (KGA) of the Packing Used, Compared to the Mass Transfer Rate of 1-1/2-in. Intalox Saddles (PKGA).

The mass transfer equation in the model was based on 1-1/2-in. Intalox saddles. Comparative KGA values can be obtained from the packing manufacturer's literature. The use of comparing mass transfer rates for various packings in the design of scrubbing systems is described by Norton (1969).

21. Actual Volumetric Gas Flow Rate (CFM) ft^3/min

22. Inlet Odor Concentration (YO) odor units

23. Outlet Concentration from the First Stage of the Scrubber (YE) odor units

24. Increment (DELTA)

    During the optimization routine, the computer model changes the liquid mass flux by this amount. Suggested value = 1,500

25. Tolerance (EPS)

    During the optimization routine, the cost is minimized until the % change in the cost for the last two iterations is less than this amount.

10.2 Scrubber Design

10.2.1 Design Equation

Consider the packed tower shown in Figure 10-1. If a material balance for an odorous compound is performed on an increment of volume within the tower, the following equation applies:

$$\begin{aligned} -G_M A dY = L_M A dX &= K_G a(P - P_i) A dZ \\ &= K_G a P_T (Y - Y_i) A dZ \end{aligned} \qquad (1)$$

where

Z is height, ft

G_M & L_M are the molar gas and liquid rates per unit area, lb moles/hr-ft^2

A is the cross-sectional area, ft^2

Y & X are mole fraction of pollutant in the gas phase and liquid phase

$K_G a$ is the mass transfer coefficient, lb moles/hr-ft^3-atm

P is partial pressure of pollutant, atm

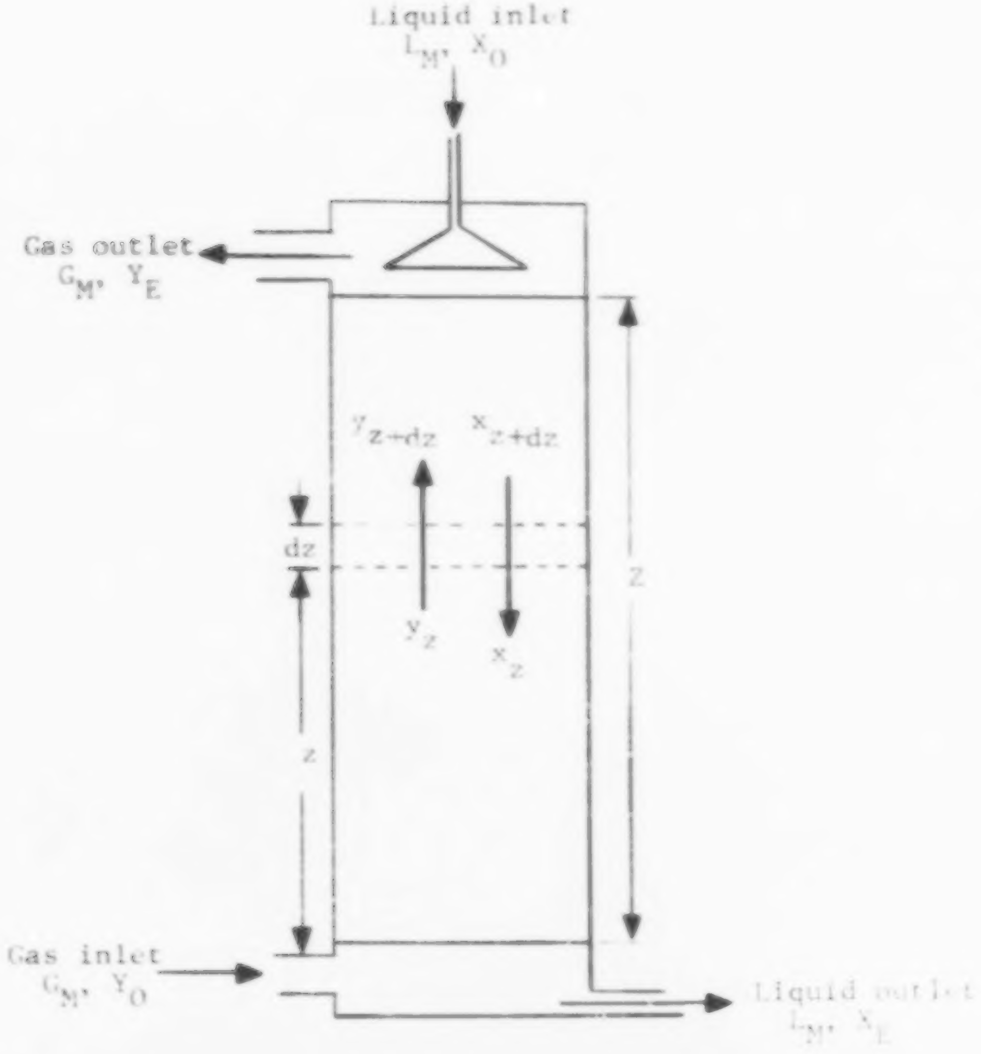

Liquid inlet
L_M, X_O
Gas outlet
G_M, Y_E
y_{z+dz}
x_{z+dz}
dz
Z
y_z
x_z
z
Gas inlet
G_M, Y_O
Liquid outlet
L_M, X_E

Figure 10-.

PACKED TOWER

P_i is the interfacial pressure of pollutant, atm

P_T is total pressure, atm

Y_i is mole fraction of pollutant in the gas at the liquid gas interface.

Eq 1 can be rearranged and integrated over the entire height of the tower:

$$Z = \int_0^Z dZ = \frac{G_m}{K_G a P_T} \int_{YE}^{YO} \frac{dY}{Y - Y_i} \qquad (2)$$

where YO and YE are the entering and exiting mole fractions of the pollutant.

For pollutants that are very soluble in the liquid phase or that react very rapidly once in the liquid phase, the mole fraction of the pollutant at the interface, Y_i, will approach zero*. (Effect of reaction rate on $K_G a$ is considered below.) Therefore:

$$Z = \frac{G_m}{K_G a P_T} \int_{YE}^{YO} \frac{dY}{Y} \qquad (3)$$

or

$$Z = \frac{G_m}{K_G a P_T} \ln\left(\frac{YO}{YE}\right) \qquad (4)$$

10.2.2 Mass Transfer Coefficient

In the final report of the previous project (Report No. EPA-R2-75-088), the mass transfer coefficient, K_G, and the wetted area fraction, "a", were separately determined. This approach was abandoned because wetted area data for

---

[*] In fact, a considerable part of the experimental work was aimed at finding purge rates and reagent concentrations for which this assumption is true.

various types and sizes of packing at different liquid and gas flow is extremely limited. From the actual mass transfer rates observed with the laboratory scrubber, a relationship was developed for the product K_Ga as a function of the following variables:

- type of packing
- size of packing
- liquid mass flux, lb/hr-ft^2
- gas mass flux, lb/hr-ft^2

10.2.2.1 Type and Size of Packing

The manufacturers' literature (U.S. Stoneware, 1963, 1970; Ceilcote) contains extensive data on the relative mass transfer rates for different types and sizes of packings. During this project, we have used Intalox saddles because of the large amount of design data in the literature for Intalox saddles.

The computer model is capable of using different types and sizes of packing. U.S. Stoneware (1963,1970) has developed mass transfer data for many types and sizes of packing. In the typical operating range, the mass transfer curves for the different packings have similar shapes.

This allows one to use the same equation, and to include a multiplier expressing the ratio of the mass transfer rate of the given packing with that of 1-1/2-in. Intalox saddles.

Thus, the mass transfer equation used to size packed towers can be written in the following form:

$$K_Ga = \text{Constant } L^aG^{-b}\text{PKGA}$$

where PKGA is the ratio of the mass transfer rates of the type and size of packing used to the rate of 1-1/2-in. Intalox saddles.

The size of the packing has a strong influence on the mass transfer rate attained; however, the pressure drop is also strongly affected. For full-scale scrubbers, 1-1/2- or 2-in. packing is normally used as a compromise between reasonable pressure drop and mass transfer rate. The cost of scrubbing with various types and sizes of packing can be explored by use of the computer model.

10.2.2.2 Liquid Mass Flux

The liquid flow rate per unit of tower area (mass flux) also has a strong influence on the mass transfer rate. As the liquid rate increases, the mass transfer rate increases, regardless of the size and type of packing. The mass transfer rate for most systems is related to the liquid mass flux by the following general relationship (Eckert, 1970)

$$K_Ga \propto (L)^{0.1-0.3}$$

For CO_2 scrubbing, the exponent for L is 0.27 (U.S. Stoneware, 1970; Perry, 1963). For many other scrubbing operations, this exponent is in the range of 0.25 to 0.29 (U.S. Stoneware, 1970). Because the effect of L on the mass transfer rate has not been experimentally investigated for odors, the value established for CO_2 removal was used for removal of rendering plant odors

$$K_Ga \propto (L)^{0.27}$$

10.2.2.3 Gas Mass Flux

The mass flux of the gas, G, refers to the flow rate per unit of cross-section of packed bed area. Since the total air flow is fixed for a given application, the mass flux determines the diameter of the scrubber chosen. It is important to know the effect G will have on the mass transfer rate, since the equipment size and cost will be strongly influenced by its effect.

The effect of the gas mass flux on mass transfer is not easy to predict. For gases such as ammonia, where the heat of solution and solubility is high (solubility 38 wt%), the gas mass flux has a significant effect on the mass transfer rate. For ammonia (Perry, 1963):

$$k_Ga \propto \left(\frac{1}{G}\right)^{0.2}$$

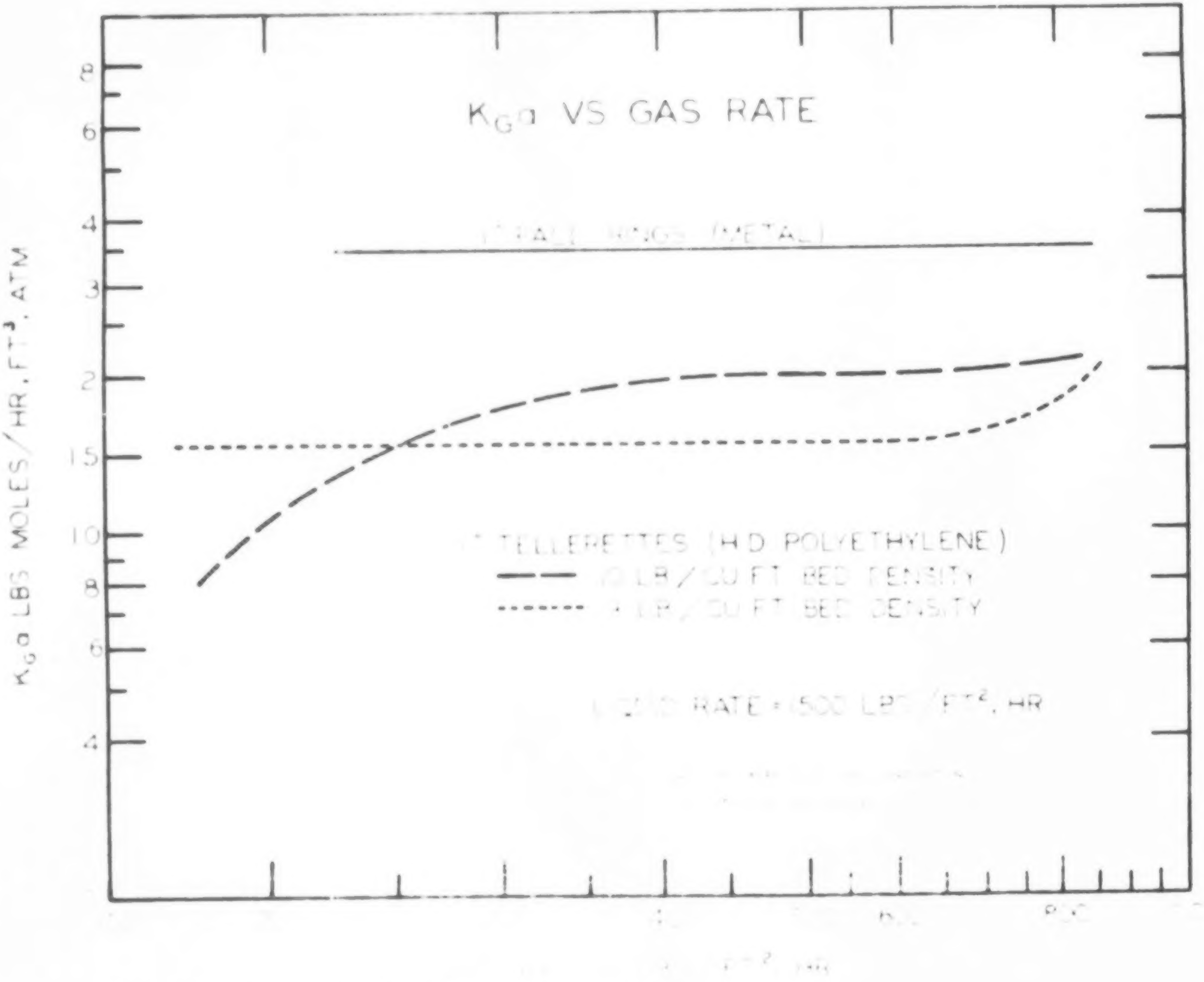
For pollutants that are not readily soluble in the liquid phase, such as CO_2 (solubility 0.169 wt% at 20°C), the mass transfer rate is not affected by the gas flux, but is determined by the amount of liquid the gas comes in contact with. Thus, in the scrubbing of CO_2 with dilute caustic, above a minimum gas flux, G has no influence on the mass transfer rate for this system.

$$K_Ga \propto \left(\frac{1}{G}\right)^{0}$$

An example of this behavior is presented in Figure 10-3 (U.S. Stoneware, 1963). The solubility of certain rendering odor compounds is low, especially for example the sulfides, and they are expected to behave like CO_2.

Test 11 was conducted with the laboratory scrubber to determine the effect of G on the mass transfer rate for rendering plant odors. The second and third stages were operated in parallel with the same liquid mass flux, but stage No. 2 had nearly twice the gas through-put. The results from this test are presented below.

	Gas Flux lb/hr/ft^2	Reduction in Odor Units	
		ED_{50} Sample Rd No. 1	ED_{50} Sample Rd No. 2
Scrubber No. 2	543	15,000 - 680	4,300 - 350
Scrubber No. 3	275	15,000 - 20	4,300 - 60



(from U.S. Stoneware, 1963)   Figure 10-2

The number of mass transfer units (NTUG) is defined as

$$NTUG = \ln(YO/YE)$$

where

YO is the inlet odor level

YE is the outlet odor level

The height of a transfer unit (HTUG) is defined as

$$HTUG = \frac{Z}{NTUG}$$

where Z is the total height of the packing. From Section 10 [illegible] the following equation was developed

$$K_Ga = \frac{G_m}{ZP_T} \ln\left(\frac{YO}{YE}\right)$$

At atmospheric pressure, and converting moles to pounds, K_Ga can be rewritten as:

$$K_Ga = \frac{G}{29\ HTUG}$$

where

29 is the molecular weight of air

K_Ga is the mass transfer coefficient, lb moles/hr-ft³-atm

G is the gas mass flux, lb/hr-ft²

HTUG is the height of a single mass transfer unit

Using the equations listed above, the following values were calculated:

Scrubber No.	G lb/hr/ft²	NTUG	HTUG (ft)	K_Ga lb moles/hr-ft³-atm
[illegible]	543	2.80	1.43	13.09
1	275	5.45	0.73	12.99

From the above table, doubling the gas throughput resulted in less than 1% change in the mass transfer rate, K_Ga. The result of this single experiment indicates that the mass transfer rate is independent of the gas mass flux, or:

$$K_Ga = \left(\frac{1}{G}\right)^0$$

10.2.2.4 Final Mass Transfer Equation

By using the data collected on the laboratory packed scrubber, a value for the mass transfer rate was determined. The development of the proportionality constant is presented in Appendix 4. The final form of the equation utilized in the model is as follows: (Note that it does not involve G, in accordance with the result just obtained)

$$K_Ga = 4.5\left(\frac{L}{1000}\right)^{0.27} \quad (PKGA)$$

For 1-1/2-in. Intalox saddles, PKGA = 1.0 by definition.

10.2.3 Correlation for Pressure Drop

The pressure drop per foot of packing is described in the following equation from U.S. Stoneware (1963).

$$P = \left(\frac{Alpha}{\rho_G}\right)(10)^{(Beta\ L)/3600}\left(\frac{G}{3600}\right)^2$$

where

P is pressure drop, in. of water

ρ_G is gas density, lb/ft^3

G is gas mass flux, lb/hr-ft^2

L is liquid mass flux, lb/hr-ft^2

Alpha, Beta are constants as given in Table 10-1.

Table 10-1

PRESSURE-DROP EQUATION FOR PARTICLE PACKING

TYPE OF PACKING	MAT'L		NOMINAL PACKING SIZE (INCHES)										
			$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{3}{4}$	1	$1\frac{1}{4}$	$1\frac{3}{8}$	$1\frac{1}{2}$	2	3
INTALOX SADDLES	CERAMIC	α			1.04		0.52	0.52			0.13	0.14	
		β			0.37		0.25	0.16			0.15	0.10	
RASCHIG RINGS	CERAMIC	α			1.96	1.31	0.82	0.53			0.31	0.23	0.18
		β			0.56	0.39	0.38	0.22			0.21	0.17	0.15
BERL SADDLES	CERAMIC	α			1.16		0.56	0.53			0.21	0.16	
		β			0.47		0.25	0.18			0.16	0.12	
PALL RINGS	PLASTIC	α						0.22		0.14		0.10	
		β						0.14		0.13		0.12	
PALL RINGS	METAL	α				0.43		0.15			0.08	0.06	
		β				0.17		0.15			0.16	0.12	
RASCHIG RINGS 1/32 WALL	METAL	α				1.20							
		β				0.28							
RASCHIG RINGS 1/16 WALL	METAL	α			1.59	1.01	0.80	0.53			0.29	0.23	
		β			0.29	0.39	0.30	0.19			0.20	0.14	

EQUATION

$\Delta p = \alpha \times 10^{\beta L}\left(\frac{G^2}{\rho_G}\right)$ (LIMITED TO REGION BELOW FLOODING)

Δp = PRESSURE DROP - INCHES OF H_2O / FT OF PACKING

G = GAS MASS VELOCITY - LBS / SEC FT^2

L = LIQUID MASS VELOCITY - LBS / SEC FT^2

ρ_G = GAS DENSITY - LBS / FT^3

α AND β = CONSTANTS

(from U.S. Stoneware, 1963)

10.2.4 Correlation for Gas Flooding Velocity

The gas flooding velocity is presented in a mathematical form by Sawistowski (1957).

$$G_F = 3600 \sqrt{\frac{GR(\varepsilon)^3 \left(\rho_L\right) \left(\rho_G\right)}{(Ap)} \left(\frac{\mu_W}{\mu_L}\right)^{0.2} \exp\left(-4\left(\frac{L}{G}\right)^{0.25}\left(\frac{\rho_G}{\rho_L}\right)^{0.125}\right)}$$

where

G_F is flooding gas mass flux, lb/hr-ft^2

GR is acceleration due to gravity, 32.2 ft/sec^2

ε is void fraction of the packing

ρ_L is density of the liquid, lb/ft^3

ρ_G is density of the gas, lb/ft^3

Ap is surface area of packing per unit volume, ft^2/ft^3

μ_W is viscosity of water (1 centipoise)

μ_L is viscosity of the liquid (centipoise)

L is liquid mass flux, lb/hr-ft^2

G is gas mass flux, lb/hr-ft^2

The values of ε and Ap for different packings are listed in Table 10-2.

10.2.5 Design Gas Flux

In order to insure stable operation and proper wetting of the packing, G is usually set at some fraction of the gas flooding rate, G_F. For Intalox saddles, G is fixed between 65-85% of the gas flooding rate (Perry 1963). Where the mass transfer rate is liquid-phase controlled, such as with odor removal using a sodium hypochlorite solution, the mass transfer rate is essentially independent of G. Thus, G should be as large as possible to minimize the tower diameter and minimize

Table 10-2

CHARACTERISTICS OF RANDOM PACKINGS*

Packing	Nominal size, in.										
	1/4	3/8	1/2	5/8	3/4	1	1 1/4	1 1/2	2	3	3 1/2
Raschig rings:											
Ceramic:‡											
C_f	1,000	750	640	380	255	160	125	95	65	37	
ϵ	0.73	0.68	0.63	0.68	0.73	0.73	0.74	0.71	0.74	0.78	
a_p	240	155	111	100	80	58	45	38	28	19	
Metal:											
1/32-in. wall:											
C_f	700		300	258	185	115					
ϵ	0.69		0.84		0.88	0.92					
a_p	236		128		83.5	62.7					
1/16-in. wall:											
C_f			340	290	230	145	110	82	57	37	
ϵ			0.73		0.78	0.85	0.87	0.90	0.92	0.95	
a_p			118		71.8	56.7	49.3	41.2	31.4	20.6	
Pall rings:											
Plastic:											
C_f				97		52		32	25		16
ϵ				0.88		0.90		0.905	0.91		
a_p				110		63.0		39	31		23.4
Metal:											
C_f				71		48		28	20		
ϵ				0.902		0.938		0.953	0.964		
a_p				131.2		66.3		48.1	36.6		
Intalox saddles, ceramic:											
C_f	600		265		130	98		52	40		
ϵ	0.75		0.78		0.77	0.775		0.81	0.79		
a_p	300		190		102	78		59.5	36		
Berl saddles, ceramic:											
C_f	900		380		170	110		65	45		
ϵ	0.60		0.63		0.66	0.69		0.75	0.72		
a_p	274		142		82	76		44	32		
Tellerettes:§	2 in., plastic										
High density:											
C_f	57										
ϵ	0.87										
Low density:											
C_f	65										
ϵ	0.83										

---

* Table from the United States Stoneware Company. Data are for wet dumped packing in 16- and 30-in. ID towers.

‡ Nominal size and wall thickness, in inches, for ceramic Raschig rings are, respectively, 1/4, 1/32; 3/8, 1/16; 1/2 to 3/4, 3/32; 1, 1/8; 1 1/4 and 1 1/2, 3/16; 2, 1/4; 3, 3/8.

§ Teller and Ford, *Ind. Eng. Chem.*, **50**, 1201 (1958).

*from Treybal, 1967)

the cost of the system. Therefore, in the computer model, $\dot{G}$ was set equal to 85% of the gas flooding rate, G_F.

10.3 Chemical Consumption

Based on the test results during this project, sodium hypochlorite with excess caustic (pH > 12) was found to be the most effective scrubbing combination. The most economical way to prepare the scrubbing solution is to purchase chlorine gas and 50% liquid caustic. The sodium hypochlorite can be purchased already prepared or it can be generated on site; however, the use of chlorine gas is more economical. On-site generation of sodium hypochlorite will be discussed in detail in Section 14.

In the model, a continuous counter-current blow-down system as shown in Figure 8-1 was assumed. As discussed in Chapters 6 and 9, the pH in the third stage must be maintained at or above pH 12. Also, as discussed in Section 7, a minimum chlorine concentration (0.17% Cl_2 was the lowest concentration tested) must be maintained in all stages for maximum odor removal.

The chemical consumption is related to the quantity of odorants removed from the air. During this program, the odor was measured both by gas chromatography and by an odor panel. The odor panel measures the odor intensity in odor units, which is the ratio of the dilution volume to sample volume required to reduce the sample to the odor threshold for 50% of the panelists (ED_{50}). Thus, odor units is an indirect measure of the concentration of odorants present in the gas stream. To obtain a measure of the quantity of odorants present, the concentration can be multiplied by the volume of air processed by the scrubber.

$$\text{Odor Quantity} = \begin{pmatrix}\text{odor units}\\ \text{removed}\end{pmatrix}(\text{ft}^3 \text{ of air treated})$$

Some of the odorous compounds removed from the gas stream will be oxidized by the hypochlorite, while some of the compounds will not react and will accumulate in the solution. Thus, the "Odor Quantity" is a measure of the oxidized by-products plus the unreacted compounds. The ability to remove these compounds from the gas into the scrubbing solution can be measured:

$$\text{Scrubbing Capacity} = \frac{\text{Odor Quantity}}{\text{Gallon of solution used}}$$

10.3.1 Chlorine Consumption

The total chlorine used is attributable to two distinct mechanisms:

1. Chlorine reacting with the odorants
2. Chlorine blow-down loss.

10.3.1.1 Chlorine Reacting with the Odorants

The amount of chlorine consumed is directly related to the odor quantity removed by the scrubber system. This chlorine consumption due to odorous compounds has been checked by using batch scrubbing tests without any blow-down. Thus by measuring the odor levels and the chlorine concentration decrease with time, a relationship was developed. This relationship, which is derived in the Appendix, is written in terms of the Odor Quantity.

$$\text{Annual chlorine consumed for odor removal} = \frac{0.32}{10^6}\text{ (Odor Quantity)}$$

where

$$\text{Odor Quantity is the} \begin{Bmatrix}\text{Average odor}\\ \text{units removed}\end{Bmatrix} \begin{Bmatrix}\text{Total volume of air}\\ \text{treated per year}\end{Bmatrix}$$

10.3.1.2 Chlorine Blow-down Loss

A certain fraction of the solution in the first stage must be continuously discharged to the sewer to purge the refractory and oxidized by products from the scrubbing solutions, and to cause a flow of liquors from stage to stage to supply chlorine needed in the first stage. It will be shown that the blow-down rate must be higher in a single-stage scrubber than with multiple stages to keep the concentration of refractory compounds low, since there are no subsequent stages to remove refractory compounds. Since the blow-down rate is higher in a one-stage scrubber, there is more wastage of reagents to the sewer and the scrubbing capacity is less.

The scrubbing capacities were experimentally determined from tests in which the scrubber was operated as a 1-, 2-, and 3-stage unit. These data are analyzed in the Appendix. The scrubbing capacities are inversely proportional to the blow-down rates. The following table was also developed in the Appendix for a scrubber treating 66,000 cfm of plant ventilating air, based on test results of both the laboratory and plant scrubber. (The scrubbing capacity values were not verified for scrubbing of high-intensity odors during the two-week test described in Chapter 9.)

Number of Stages	Scrubbing Capacity	Required Blow-down Rate
3	14×10^6	2 gpm
2	7×10^6	4 gpm
1	3×10^6	9 gpm

The chlorine wasted to the sewer is a function of the blow-down rate and the chlorine concentration maintained in the first stage. Figures 10-3 and 10-4 show the chlorine levels in all three stages for the plant and laboratory life tests. The concentration of chlorine in the first tank equals the concentration of chlorine in the blow-down to the sewer. From the figures and using the blow-down rates that were used for each life test, the amount of chlorine lost to the sewer was computed. For the three-stage scrubber tests performed using the continuous blow-down, 8% of the chlorine was lost to the sewer.

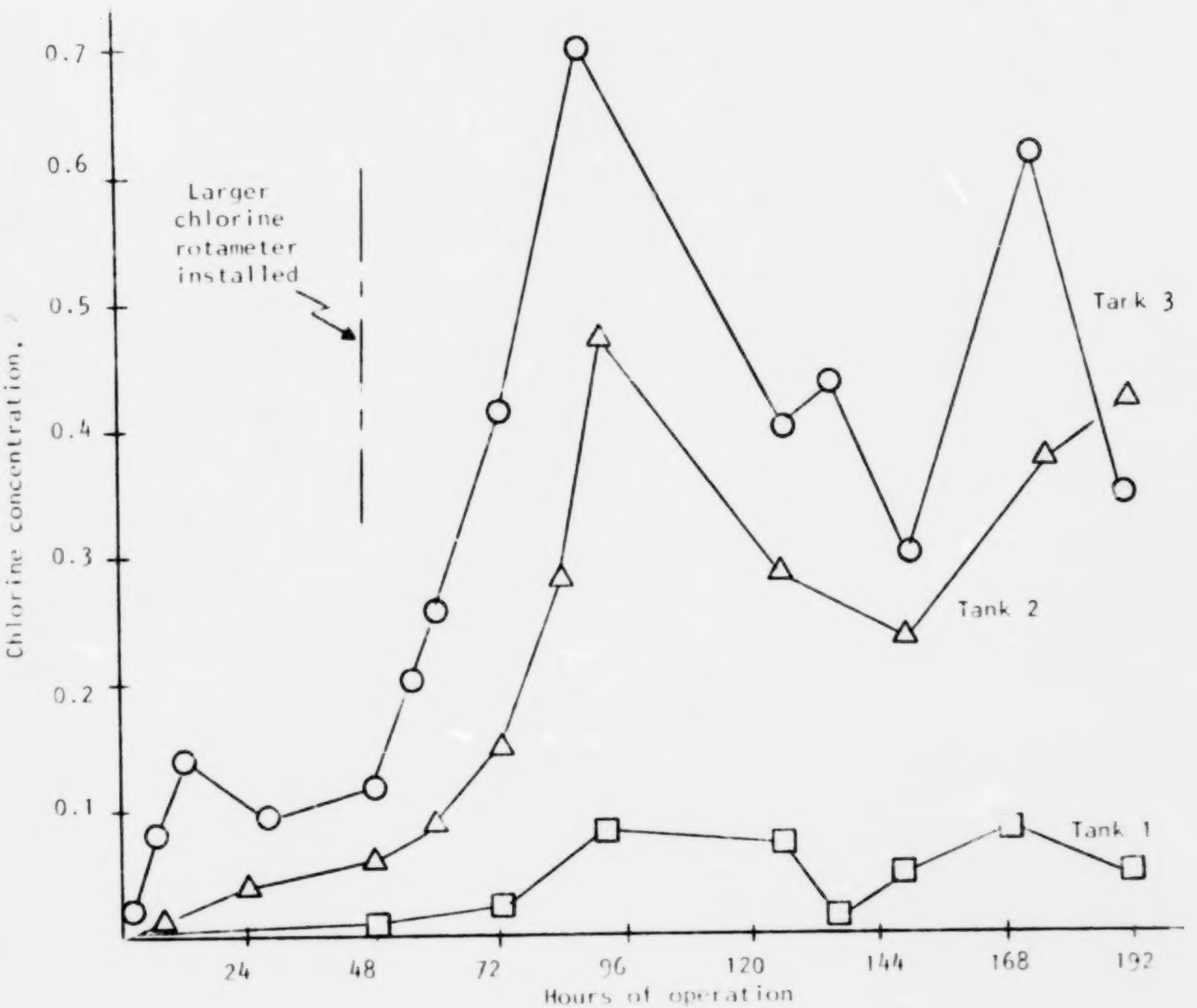

CHLORINE RESIDUAL VS TIME
(Test 34)

Figure 10-3

PLANT SCRUBBER CHLORINE LEVELS

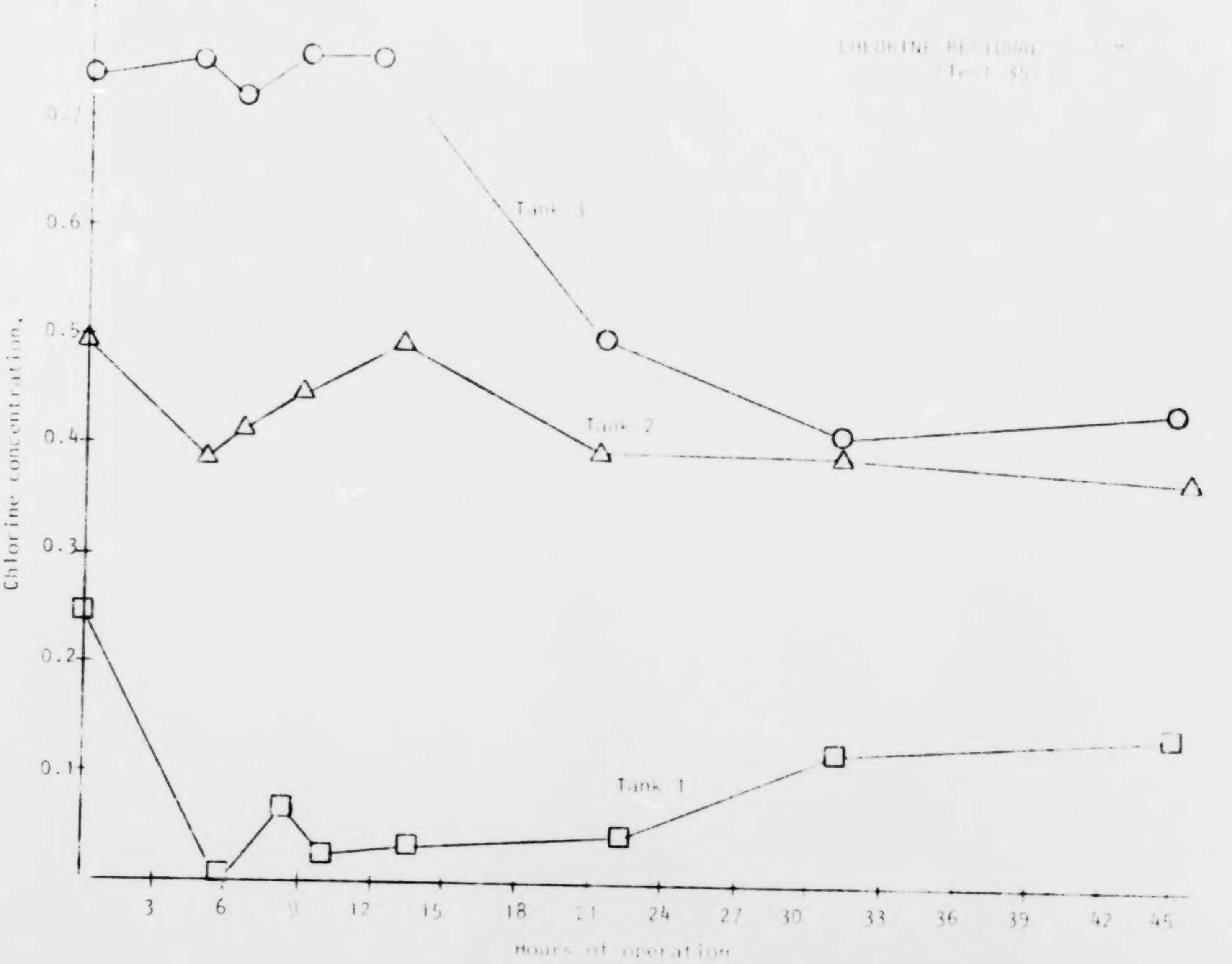


Figure 10-4.

LABORATORY SCRUBBER CHLORINE LEVELS

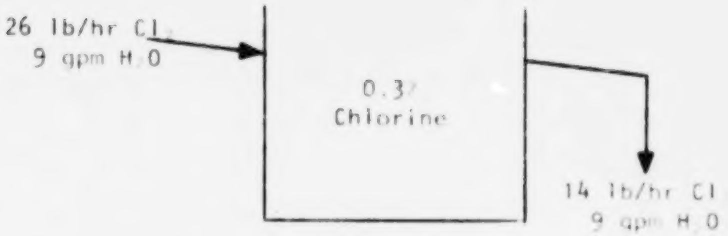
In a one-stage system, the blow-down rate is very high compared to a three-stage system. The amount of chlorine lost to the sewer will depend on the chlorine concentration maintained in the tank. In a one-stage system, if the chlorine level falls due to fluctuating odor concentrations, there is not the back-up of the following stages. In a one-stage system, it is imperative that a chlorine residual is always present, but the required residual is not known exactly. As a reasonable compromise between maintaining a chlorine residual and wasting excessive chlorine to the sewer, a chlorine concentration of 0.3% was assumed in the one-stage model. More research is needed to better define the minimum chlorine level that is required.

For a two-stage system, the chlorine residual in the first stage should be maintained somewhere between the levels used for the one- and the three-stage systems. The model uses 0.2% chlorine in the first stage as the chlorine control in the two-stage system. Figure 10-5 shows the chlorine levels for all three scrubber systems. Using Figure 10-5, the percent chlorine lost to the sewer was computed:

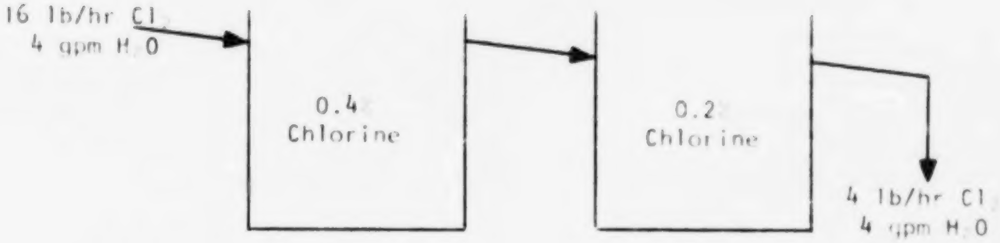
	Chlorine loss
1 stage	54%
2 stages	25%
3 stages	8%

As stated earlier, the blow-down rate is determined by the odor quantity removed. The above percentages must be converted to pounds of chlorine consumed. This can be done by relating the chlorine loss to the chlorine consumed for odor removal. The derivation is presented in the Appendix with the final equation shown below:

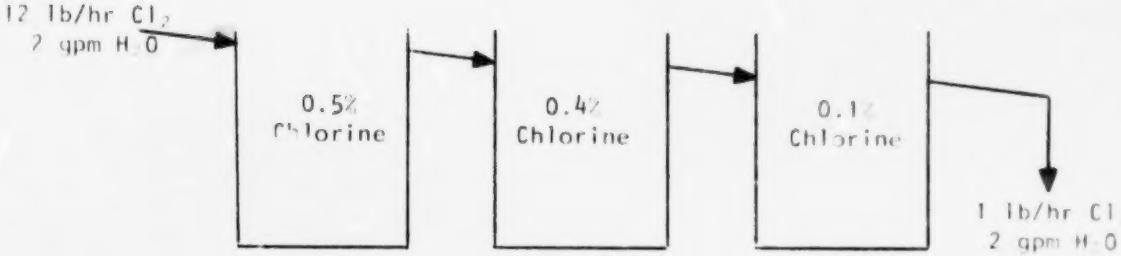
$$\text{Annual chlorine loss to sewer} = \left[\text{Annual chlorine for odor removal}\right] 4.2 \exp(-1.28NS)$$


26 lb/hr Cl2
9 gpm H2O
0.3%
Chlorine
14 lb/hr Cl2
9 gpm H2O

1-stage system


16 lb/hr Cl2
4 gpm H2O
0.4%
Chlorine
0.2%
Chlorine
4 lb/hr Cl2
4 gpm H2O

2-stage system


12 lb/hr Cl2
2 gpm H2O
0.5%
Chlorine
0.4%
Chlorine
0.1%
Chlorine
1 lb/hr Cl2
2 gpm H2O

3-stage system

Figure 10-5

CHLORINE CONSUMPTION RATES FOR SCRUBBER DESIGN MODEL

10.3.1.3 Total Chlorine Consumption

The total chlorine consumed is the sum of the chlorine utilized plus chlorine lost.

Annual chlorine = Annual chlorine consumed for odor removal
+ annual chlorine loss to sewer

Note that only the chlorine loss to the sewer is a function of the number of stages.

10.3.2 Caustic Consumption

Caustic consumption is attributable to four distinct mechanisms.

1. Caustic consumption due to reaction with chlorine make-up.
2. Caustic consumption due to CO_2 absorption.
3. Caustic consumption due to reaction with odorous compounds.
4. Caustic consumption required to raise the pH of the incoming water to 12.

10.3.2.1 Caustic Consumption Due to Chlorine Reaction

The caustic consumption for reaction with chlorine make-up is directly proportional to the chlorine used, as shown by the following reaction.

$$Cl_2 + 2NaOH \rightarrow NaOCl + NaCl + H_2O$$

For every mole of chlorine (71 lb) consumed, 2 moles of caustic (2 x 40 lb) will be used to form sodium hypochlorite. Thus, the following relationship can be used for predicting this part of the caustic consumption:

Annual NaOH for Cl_2 = 1.12 x (annual chlorine)

10.3.2.2 Caustic Consumption Due to CO_2 Removal

Some caustic is consumed by reacting with the CO_2 scrubbed from the air. This caustic consumption will be a function of the air flow rate and is independent of the odor level. Data (Eckert, 1970) for CO_2 scrubbing shows that the removal is not complete, but increases with increasing pH of the caustic solution. Thus, CO_2 absorption varies directly with the NaOH concentration and the amount of Na_2CO_3 in equilibrium with the NaOH. The equilibrium between NaOH and Na_2CO_3 depends on the caustic blow-down and make-up rates.

From the plant test using the continuous blow-down system, it was observed that when the final stage was near pH 12, there was a drop in pH to the next stage of over 2 pH units. In aqueous caustic at pH 12 there is 0.04% free NaOH. At pH 10, there is only 0.0004% free NaOH. Thus, in the scrubber system, the amount of free caustic in the first and second stages is negligible compared to the caustic in the third stage.

Eckert (1970) presented mass transfer rates for CO_2 removal using various concentrations of NaOH and Na_2CO_3. With 0.05% free NaOH and assuming 0.25% Na_2CO_3 in the solution, a mass transfer coefficient K_Ga of 0.19 lb moles/(hr-ft^2-atm) is obtained from Eckert's data. In Section 10.2.2, the mass transfer rate for odorous compounds was developed. For 1-1/2-in. Intalox saddles, the mass transfer rate is typically 7 lb-moles/(hr-ft^2-atm). In these experiments, the system was designed to remove 90% of the odor units. Such a system would also remove:

$$CO_2 \text{ removal} = 0.9 \frac{K_Ga\ CO_2}{K_Ga \text{ odorants}} = 0.9 \frac{0.19}{7.0} = 2.4\%$$

A system designed to remove 90% of the odorous compounds will remove 2.4% of the CO_2, or 0.8 lb CO_2 per 10^6 ft^3 of air. If it were not for this mass-transfer limitation, the CO_2 in the air would neutralize much greater amounts of caustic.

For every lb-mole of CO_2 removed, 2 lb-moles of caustic are consumed, or 1.44 lb NaOH/10^6 ft^3 of air. The above equation is for 90% removal; a generalized model is presented below:

$$\text{Annual NaOH for } CO_2 = \frac{42}{10^6}(\text{CFM})(\text{NTUG})(\text{HRS})$$

where

CFM is volumetric air flow rate, ft^3/min

NTUG is number of transfer units per stage $= \ln(YO/YE)$

HRS is number of hours per year the scrubber is operated.

10.3.2.3 Caustic Consumption Due to Reaction with Odorants

By comparing the liquor life tests on the plant and laboratory scrubbers, a good indication of the caustic consumption due to reaction with odorous compounds can be obtained. This caustic consumption is a function of the odor levels and gas throughput. The following relationship was developed from the life tests performed in Test 32. The derivation is presented in the Appendix.

$$\text{Annual NaOH for odor removal} = (YO - YE)\left(\frac{\text{CFM}}{1{,}000{,}000}\right)(\text{HRS})(0.10)$$

where

CFM is the volumetric air flow rate, ft^3/min

YO is the inlet odor concentration, odor units

YE is the scrubber outlet odor concentration, odor units

HRS is the number of hours per year scrubber is in operation.

10.3.2.4 Caustic Consumption Required to Raise the Incoming Water to pH 12

The make-up water must be raised to pH 12 to maintain the pH in the last stage, where the make-up is introduced.

The make-up rate is equal to the blow-down rate.* In distilled water, 0.01 Normal NaOH has a pH of 12. In a typical tap water 0.015 Normal NaOH will be required for pH 12. Thus, 0.015 Normal or 0.06% by weight NaOH must be introduced into the make-up water to maintain the pH. The water blow-down rate times 0.06% will yield the lb of caustic required.

$$\begin{array}{r} \text{Annual NaOH for} \\ \text{make-up water} \end{array} = \begin{array}{c|c|c|c|c} 0.0006 & \text{blow-down rate, gal} & 8.34\ \text{lb} & 60\ \text{min} & \text{HRS} \\ \hline & \text{min} & \text{gal} & \text{hr} & \end{array}$$

$$= (0.3)(\text{HRS})(\text{Blow-down rate, gpm})$$

10.3.2.5 Total Caustic Consumption

The annual caustic consumption is the sum of the four items presented above.

Total lb NaOH/yr

Annual NaOH for Cl_2
+ Annual NaOH for CO_2
+ Annual NaOH for odors
+ Annual NaOH for make-up water

10.3.3 Design Odor Levels for Calculations

A scrubbing system should be designed to handle the maximum odor levels anticipated; however, when computing annual chemical costs, the average odor levels anticipated should be used.

In order to satisfy both the design and the chemical cost requirements, the inlet odor levels are the anticipated average levels, but the desired outlet values are lower than needed. Thus, the scrubbers are designed with the necessary mass transfer units (NTUG) for handling maximum odor levels.

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* The make-up rate also must include any water lost through evaporation; however, no caustic is required for the evaporation loss because the caustic is left in solution when the water evaporates.

10.4 Costs

10.4.1 Capital Costs

This section details the cost equations used in the computer model. The equations include the purchase and installation costs for the entire system. All cost data taken from the literature were changed to 1957-1959 costs; these are then multiplied by the Cost Index to convert to current costs.

10.4.1.1 Tower

The purchased cost of fiberglass reinforced plastic towers is given by Ceilcote (1973). The installation cost of the towers was developed using construction data presented by Popper (1970). Included in the installation cost is the concrete, piping, structural support, instrumentation, electrical, and labor costs. The installation portion of the cost was assumed independent of the material of construction.

The equation derived from the data provided by Popper and Ceilcote for one tower is presented below:

$$\text{Tower}(1) = (51[\text{MCF}] + 69)(\text{CI})(\text{Diam})^{1.2}(Z + 4)^{0.65}$$

where

MCF is material cost factor

CI is cost index

Diam is diameter of the tower, ft

Z is packing depth, ft

Tower(1) is installed cost of the tower, \$

As the tower diameter increases above 10 ft, the installed cost increases much faster as a function of diameter. This is because the tower will have to be field fabricated. Structural support costs will also increase much faster than diameter. Thus, for towers greater than 10 ft, the following relationship was used.

$$\text{Tower}(1) = [12(\text{MCF}) + 16](\text{CI})(\text{Diam})^{1.85}(Z + 4)^{0.65}$$

Using Popper's cost estimating technique, it was estimated that additional installed towers would cost 80% of the first tower. Thus, the total cost of a multiple tower installation is:

$$\text{Tower} = \text{Tower}(1) + (\text{NS} - 1)(0.8)[\text{Tower}(1)]$$

10.4.1.2 Tanks

The size of the liquid holding tanks is a function of the liquid pumping rate. The following relationship was developed, assuming a holding capacity equal to four times the liquid pumping rate (4 x GPM) and data supplied by Ceilcote (1973).

$$\text{Tanks} = 300(\text{CI})(\text{NS})(\text{MCF})\left(\frac{\text{GPM}}{60}\right)^{0.6}$$

where

Tanks is installed cost of the tanks, $

CI is cost index

NS is number of stages

MCF is material cost factor

GPM is liquid pump rate, gal/min

10.4.1.3 Internals

The internals include a demister, a liquid distribution system, and a support plate for the packing for each stage. The cost relationship for the internals was also developed from data supplied by Ceilcote (1973).

$$\text{Internals} = 3.38(\text{CI})(\text{NS})(\text{Diam})^{2.6}$$

where Internals is installed cost of the internals, $.

10.4.1.4 Fan

The installed cost of the fan, excluding the motor, is a function of the gas throughput (Aries et al., 1955). The assumption was made that only one fan would be required regardless of the number of stages. Aluminum fan blades coated with glass-reinforced vinyl ester to resist corrosion were assumed.

$$\text{Fan} = 0.25(\text{CI})(\text{CFM})^{0.77} + 50$$

where

Fan is installed cost of the fan, \$

CFM is gas flow rate, ft^3/min.

10.4.1.5 Pumps

Each stage of the scrubber will have its own centrifugal stainless steel pump. The installed cost of all the pumps, excluding motors, is a function of the liquid flow rate (Popper, 1970).

$$\text{Pump} = 9(\text{NS})(\text{CI})(\text{GPM})^{0.6} + 50$$

where

Pump is installed cost of the pumps, \$

GPM is liquid flow rate in each stage, gal/min.

10.4.1.6 Motors (Open Type)

The cost of the motors required for the liquid pumps and the fan is a function of the horsepower required (Peters et al., 1968)

$$\text{Motors} = 350(\text{CI})\left(\frac{\text{HP}_{\text{pump}}}{10}\right)^{0.67}(\text{NS}) + 350(\text{CI})\left(\frac{\text{HP}_{\text{fan}}}{10}\right)^{0.67}$$

where

Motors is installed cost of all the motors, \$

NS is number of stages in the scrubber

HP_{pump} is pump horsepower

HP_{fan} is fan horsepower

CI is cost index

10.4.1.7 Packing

The packing cost is a function of the packing volume and the unit cost of the packing.

$$\text{Packing} = (NS)(CPA)(\text{Volume})$$

where

Packing is installed cost of the packing, \$

CPA is unit cost of the type and size of packing, $\$/ft^3$

Volume is packing volume of each stage

NS is number of stages.

10.4.2 Operating Costs

10.4.2.1 Pump Horsepower

The power required for pumping the liquid to the top of the tower is given by:

$$HP_{pump} = \frac{8.34(Z + 10)(GPM)}{3.3 \times 10^4 \; EP}$$

where

HP_{pump} is pump horsepower requirement

Z is packing depth, ft. 10 ft is allowed for distributor level above packing and miscellaneous pressure losses

GPM is liquid pumping rate, gal/min

EP is efficiency of the pump

10.4.2.2 Fan Power

The power required to draw the gas through the entire scrubber is

$$HP_{fan} = 1.57 \times 10^{-4} \Delta P \left(\frac{CFM}{EF}\right)$$

where

HP_{fan} is fan horsepower requirement

ΔP is pressure drop across the entire scrubber, in. of H_2O

CFM is volumetric gas flow rate, ft^3/min

EF is efficiency of the fan

10.4.2.3 Power Cost

The annual cost of power is

$$Power = 0.746(HRS)(HP)(CE)$$

where

Power is annual power cost, $

HRS is the number of hours in operation per year

0.746 is conversion factor from HP to kwatts

CE is cost of electricity, $/KWH

HP is the total power required for the pumps and the fan

10.4.3 Chemical Costs

The cost of buying chlorine gas and sodium hydroxide depends upon the quantity purchased and the location of the plant. A major part of the cost of both chemicals is the delivery charge. For the computer model, the assumption was made that chlorine would be purchased in one-ton cylinders for $0.11/lb. The caustic, delivered in tank truck loads will cost $0.085/lb of sodium hydroxide. (These costs are higher than the tank-car prices ($0.05/lb) which are often quoted.) In order to purchase the caustic at \$0.085, a 2,500-gal caustic storage tank will be necessary; the cost of such a storage tank is not included in the computer model. The cost figures used in the model are the expected prices in the Chicago area during the next year (K. A. Steel, 1974).

10.4.4 Maintenance Cost

As the size of a scrubber system increases, so does the maintenance cost. In addition, as the number of stages increases, the required maintenance will also increase. The annual maintenance cost assumed in the model is presented below:

$$\text{Maint} = \text{CM}\sqrt{\text{CFM(NS)}}$$

where

Maint is annual maintenance cost, \$

CM is maintenance cost factor, used 8 in this study

CFM is gas throughput, ft^3/min

NS is number of stages.

10.5 Scrubber Design and Cost Estimate Results

With the computer model described in the previous sections, the least-cost design can be computed. In order to use the model, the user must specify the number of packed towers in series, the desired inlet and outlet odor level in odor units, the gas volumetric flow rate, and the number of hours in operation per year. In addition, the user must specify the type of material of construction and the current construction cost index.

A series of packed scrubber designs were calculated for various volumetric flow rates and odor levels. A construction cost index of 1.75 was used; this is the estimated index for December 1974 (Chemical Engineering). Fiberglass reinforced plastic was selected as the material of construction for the packed towers. Vinyl ester resin is recommended for alkaline hypochlorite solutions by Dow Chemical Co. Intalox saddles (1-1/2-in.) were selected for the packing because their mass transfer/pressure drop behavior is one of the best available. In addition, 4,000 hours of operation per year was assumed for the scrubber.

The model reflects the current state-of-the-art in regard to type and quantity of chemicals consumed and in regard to the mass transfer rate. Most of the chemical consumption and mass transfer data were obtained using both the plant scrubber and the laboratory packed scrubber at Des Moines.

10.6 Discussion of Computed Costs

The results at 4,000 hours per year are presented for various conditions in Tables 1 through 14 in Appendix 5. The results are summarized in Table 10-3 and the optimum design under each set of conditions is presented in Table 10-4. As would be expected, the cost per 1,000 cfm-hr decreases as the gas throughut increases. Tables 10-3 and 10-4 also show that the cost per 1,000 cfm-hr increases from $0.23 to $0.39 for 50,000 cfm as the inlet odor level increases, due to the increase in chemical consumption.

There are two major costs in using packed scrubbers in odor control; the initial capital investment and the chemical cost. One major assumption used in the model was that the same liquid reagents will be used in each stage. Thus, by operating the liquid tanks countercurrent to the air flow, as shown in Figure 8-1, the chemical consumption can be reduced. On the other hand, a single-stage scrubber can provide a larger mass transfer volume at a lower capital cost than a multiple-stage scrubber; but, it cannot bleed the liquid from stage to stage countercurrently. For odor levels that average less than 500 odor units, a single-stage packed

Table 10-3

PACKED TOWER COST SUMMARY
1-1/2-IN. INTALOX SADDLES

Flow, cfm	Average odor units		Design maximum odor units		Number of stages	Capital investment, $	Chemical cost, $/yr	Total annual cost, $/yr	$/1000 cfm-hr*
	Inlet	Outlet	Inlet	Outlet					
5,000	8,000	40	50,000	250	1	25,800	25,000	29,800	1.49
					2	33,600	15,800	22,000	1.10
					3	39,500	13,100	20,400	1.02
10,000	8,000	20	50,000	125	3	67,200	26,300	39,200	0.98
25,000	500	10	5,000	100	1	75,700	9,000	23,700	0.24
					2	96,100	5,500	24,100	0.24
					3	113,700	4,500	26,400	0.26
25,000	2,000	20	10,000	100	1	83,800	32,300	48,500	0.48
					2	103,100	20,200	40,500	0.40
					3	120,800	16,700	40,500	0.40
50,000	500	10	5,000	100	1	144,200	18,000	45,700	0.23
					2	181,400	11,000	46,000	0.23
50,000	1,000	20	10,000	100	2	197,800	40,400	78,600	0.39
					3	230,300	33,400	78,200	0.39

*Based on 4,000 hours of operation per year and equipment depreciated 13% a year using the straight-line depreciation method. See AMF factor, p. 10-3.

Table 10-4

OPTIMUM DESIGN OF PACKED TOWERS*
1-1/2-IN. INTALOX SADDLES

Flow, cfm	Average odor units		Number of stages	Flow rates, lb/hr/ft^2		Packing depth, ft	Diameter, ft	\$/1000 cfm-hr†
	Inlet	Outlet		Liquid	Gas			
5,000	8,000	40	3	4750	1100	9.7	5.1	1.02
10,000	8,000	20	3	4750	1100	11.0	7.2	0.98
25,000	500	10	2	5125	1060	10.3	11.6	0.24
25,000	2,000	20	3	4000	1180	9.6	11.0	0.40
50,000	500	10	2	4750	1100	10.8	16.2	0.23
50,000	2,000	20	3	4000	1180	9.6	15.6	0.39

†Based on 4000 hours of operation per year and equipment depreciated 13% a year using the straight-line depreciation method.

*Optimum combination selected based upon annual rate of return on incremental capital expenditure for additional stages. For example,

$$\text{Annual rate of return for 3 stages, instead of 2 stages} = \frac{\Delta(\text{Operating cost, 2-3})}{\Delta(\text{Capital expenditure, 3-2})}$$

Assumed a minimum annual rate of return of 10% required for additional stages.

tower will be the most economical, according to the calculations. Above an average inlet odor level of approximately 2,000 odor units, the economics favor a three-stage system.

Packed scrubbers offer a viable alternative to incinerators for gas streams containing high concentrations of odorous compounds. In some cases, a higher capital expenditure will be required for a scrubber system (Doty, et al., 1972), but the savings in fuel costs more than offset any increase in capital expenditure. One potential use of a packed scrubber would be treating the non-condensibles in the cooker off-gas. Scrubbing of concentrated odor streams can result in substantial savings as compared to incineration. For example, a three-stage 10,000 cfm scrubber treating the cooker off-gas would use $26,300 of chemicals a year, compared to an incinerator, which would use $64,000 of natural gas[1] each year. Thus, the savings of a scrubber system can be substantial. A further savings can be attained by incorporating a small packed tower for the concentrated odor streams, with a ventilating spray scrubber for the entire plant. The concept of a total scrubbing system is developed in Chapter 12.

The cost data presented in this section was based upon performance tests at a rendering plant. However, test 35, which was performed to verify the computer model, was unsuccessful, due to the low water and chemical make-up rates used. The water and chemical make-up rates were increased for the model based upon the results of test 35; however, these new rates have not been verified. Therefore, the chemical costs presented in this section are only estimates and not actually measured rates.

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[1] Assumes a natural gas price of $1.00/1,000 scf.

11. DESIGN AND COST OF HORIZONTAL SPRAY SCRUBBERS

11.1 Introduction

A computerized design procedure for horizontal spray scrubbers was developed in the previous project (Report EPA-72-R2-088). This model has been revised based on the information collected at the rendering plant in Des Moines during this project. The model is based on the spray scrubber design of Air Conditioning Corporation, Greensboro, North Carolina, but variations in the design are explored.

The scrubber consists of a large duct which varies in size with the gas throughput, into which the plant air flows, as shown in Figure 3-2 (page 3-4). A bank of spray nozzles is mounted near the entrance of the duct. The liquid is pumped under pressure (5-10 psig) through the spray nozzles, where the scrubbing liquid is atomized. The model uses the penetration theory to calculate the mass transfer of odorous compounds from the gas phase to the liquid droplets. Performance data collected on the spray scrubber at Des Moines was compared with the predicted performance from the model in Appendix 3. The penetration theory model predicted the dimensions of the spray scrubber within 13% of the actual dimensions using the Des Moines performance data as input. A detailed description of the penetration theory is provided in Report EPA-R2-72-088 and a summary is given in Appendix 3.

11.2 Nozzle Pressure Effect on the Mass Transfer Rate

In the earlier computer model, the mean droplet diameter was assumed constant at 400 μm. The mean droplet size is not constant, but a function of the nozzle pressure and the liquid flow through each nozzle. The actual effect of the pressure and flow rate on droplet size will depend on the nozzle design. Data from the Delavan Manufacturing Company (1972) and the

Spraying Systems Company (1966) were averaged to develop the following relationship.

$$D_{Drop} = 400\left(L_{NOZ}\right)^{0.17}\left(\frac{10}{PSI}\right)^{0.23}$$

where

D_{Drop} is mean droplet diameter, μm

L_{NOZ} is liquid flow rate through the nozzle, gpm

PSI is pressure across the nozzle, lb/in.^{2}

Using the above relationship, the mass transfer rate can be determined using the penetration theory based on the transient diffusion of odorant through the gas layer adjacent to each drop, given in Appendix 3. During this project, an attempt was made to verify the above model and its effect on the mass transfer rate.

In the last stage of the plant scrubber, all 270 of the coarse nozzles (1/4-in. orifice) were replaced by finer (1/8-in. orifice) nozzles to produce a smaller droplet size. The liquid flow through both stages was adjusted to the same rate; so that the only variation would be the finer spray in the third stage. The nozzle pressures were 18 psig and 26 psig in the second and third stages, respectively. The scrubber was operated as a two-stage scrubber, using the first two stages (both coarse nozzles) and then using stages 1 and 3 (with fine nozzles in stage 3).

Prior to the test, 3 gallons of caustic were added to the first stage, and 14 gallons of caustic were added to the second and third stages. Chlorine was added to just the second and third stages. At the beginning of the test, the following conditions were measured.

	pH	% chlorine
Tank #2	11.25	0.157
Tank #3	11.25	0.147

For the first half-hour of the test, the third stage was turned off and the performance of the original low pressure nozzles was measured. Then, after the first half-hour, the second stage was turned off and the third stage was placed in service with the first stage. The results from this test are presented in Tables 11-1 and 11-2.

The inlet odor level averaged 4,700 odor units during the first half of the test, but only averaged 265 odor units for the second half of the test. The large variation in the inlet odor levels makes any conclusion that can be drawn very questionable. The finer nozzles removed an average of 80% of each component as compared to 75% for the coarse nozzles; however, the reduction in odor units was much higher for the low pesssure nozzles, primarily due to the very high inlet odor level.

The equation for the droplet diameter developed from the literature shows that the droplet diameter does not change much with increasing pressure; however, the pumping cost increases directly with nozzle pressure. To increase the mass transfer rate, it is more economical to increase the number of nozzles and operate at the lowest operable pressure drop (10-15 psig) across the nozzles, rather than to increase the nozzle pressure. In addition, the finer nozzles are more susceptable to plugging. Thus, the maintenance cost for cleaning finer nozzles is higher.

The mass transfer data developed for horizontal spray scrubbers was verified using the plant scrubber in Des Moines with the coarse nozzles. The limited data available indicates that these are more economical than fine nozzles operating at higher pressure.

11.3 Other Model Modifications

The cost equations have been modified to include the construction cost index and material cost factor as described in

Table 11-1

RESULTS OF SCRUBBING TEST 36 - COARSE NOZZLES
PLANT SCRUBBER

	Inlet	Outlet	% removal
Odor ED_{50}	4700	160	97
GLC peaks, μg/liter air			
1. Dimethyl sulfide	1.31	0.39	70
2. Pungent U.P. 90	-	-	-
3. Dimethyl disulfide	-	-	-
4. Butyric acid	0.52	0.09	83
5. Propylene sulfide (cabbage 880)	-	-	-
6. Bitter 655	-	-	-
7. Burnt 1233A (pyrazine)	-	-	-
8. Burnt 1233B (pyrazine B)	1.15	0.27	77
9. Rendering 1335	35.06	7.78	78
10. Fatty 1545	4.39	1.51	66
11. Burnt 1687 (quinoline)	-	-	-
12. Sulfur 660	-	-	-
13. Cheesy 2002	-	-	-
14. Unpleasant 2582	-	-	-
15. Fatty acid 1980	3.79	0.85	78
16. Fatty acid 2160	-	-	-
Average percent removal of each component			75

Table 11-2

RESULTS OF SCRUBBING TEST 36 - FINE NOZZLES
PLANT SCRUBBER

	Inlet	Outlet	% removal
Odor ED_{50}	265	110	58
GLC peaks, μg/liter air			
1. Dimethyl sulfide	0.54	0.21	61
2. Pungent U.P. 90	-	-	-
3. Dimethyl disulfide	-	-	-
4. Butyric acid	0.08	<0.01	90
5. Propylene sulfide (cabbage 880)	-	-	-
6. Bitter 655	-	-	-
7. Burnt 1233A (pyrazine)	-	-	-
8. Burnt 1233B (pyrazine B)	0.34	0.02	94
9. Rendering 1335	7.95	0.69	91
10. Fatty 1545	7.74	0.08	99.0
11. Burnt 1687 (quinoline)	-	-	-
12. Sulfur 660	-	-	-
13. Cheesy 2002	-	-	-
14. Unpleasant 2582	-	-	-
15. Fatty acid 1980	0.13	0.07	46
16. Fatty acid 2160	-	-	-
Average percent removal of each component			80

Section 10.1. The cost equations are the same ones presented in the packed tower section (10.4), except for the scrubber cost. The spray scrubber cost equations are the same as used in the previous project (except that a misunderstanding about the length of a scrubber module has been corrected). The chemical consumption equations are the same ones developed in Section 10.3 for the packed towers.

11.4 Spray Scrubber Design and Cost Estimate

The computer model is programmed to determine the least-cost design by varying the liquid flow rate through each nozzle. For each liquid flow rate, the scrubber cross-sectional area required to obtain the specified removal is then calculated. Assuming the scrubber height and width are equal, the scrubber cost is then determined for each given liquid flow rate per nozzle. After completing the costs for five different liquid flow rates, the least cost design is then selected by the computer program. There are several other variables that will have an effect on the least cost design and which must be specified in the input. Each of these variables is discussed in the following paragraphs.

The nozzle density or the number of nozzles per square foot will have an affect on the optimum design. In general, a high nozzle density is desirable; this will allow for a lower liquid flow per nozzle and a lower pressure drop across the nozzles. The nozzle density and the flow rate per nozzle are inversely proportional for a given total liquid flow. Because the flow rate per nozzle is varied in the program, the nozzle density was held constant for this work at 6 nozzles/ft^2.

As with packed towers, the mass transfer rate increases with increasing contact time between the liquid and the gas. In this model, the contact chamber length is specified, and the chamber cross-sectional area is calculated for the desired odor reduction. The actual chamber lengths used for any installation will depend upon the available space for the scrubber. The capital investment for a longer contact chamber is about the same as for the shorter chamber because of the resulting difference in the cross-sectional area. Thus, available space will be the prime factor in determining the contact chamber length.

Table 11-3 is a summary of the computer runs performed under various conditions. The optimum design for each flow rate and odor level is presented in Table 11-4. The actual computer output for each set of conditions is shown in Tables 15 through 29 in Appendix 5. The optimum capital investment varies from \$2/cfm for a 25,000 cfm unit to \$1.43/cfm for a 150,000 cfm scrubber. These capital investments are for type 316 stainless steel scrubbers*, plus all of the necessary auxiliary equipment. The optimum design for all conditions is a multiple-stage scrubbing unit, reflecting the significant chemical cost savings with multiple-stage units. At the higher inlet odor levels, the three-stage units are the most economical. Where the average inlet odor level is greater than 1000 odor units, the third stage is economically justifiable; below 1000 odor units, a two-stage unit should be purchased.

In one set of conditions, the nozzle pressure was increased to 25 psi. No change in the capital investment was calculated with the higher pressure; however, the electricity cost increased \$330/yr, for a 25,000-cfm scrubber. The increase in electrical costs would be proportionately greater for larger scrubbers.

A comparison of the cost of spray scrubbers with the costs of packed towers reveals that packed towers are more expensive. The chemical and operating costs are about the same, but the major difference is in the inital capital investment. Packed

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*The use of stainless steel in scrubbers presents corrosion problems. An alternative material is discussed in Chapter 15. Stainless steel was used in the model because cost data are readily available, and this is the material currently being used.

Table 11-3

SPRAY SCRUBBER COST SUMMARY

Flow, cfm	Average odor units Inlet	Average odor units Outlet	Number of stages	Chamber length, ft	Total length, ft	Nozzle pressure, psi	Scrubber height and width, ft	Chemical cost, $	Capital investment, $	Total cost, $/yr	$/1000 cfm-hr*
25,000	500	10	1	8	20	15	5.6	9,000	39,200	17,700	0.18
			1	16	28	15	4.7	9,000	39,200	17,400	0.17
			2	8	36	15	4.8	5,500	49,800	17,100	0.17
			2	16	52	15	3.7	5,500	47,700	16,800	0.17
			2	16	52	25	3.8	5,500	47,800	17,100	0.17
			3	8	52	15	4.2	4,500	57,500	18,500	0.18
25,000	2000	20	1	8	20	15	5.9	32,300	40,900	41,400	0.41
			2	8	36	15	5.1	20,200	52,100	32,300	0.32
			3	8	52	15	4.4	16,700	60,100	31,300	0.31
50,000	500	10	2	8	36	15	7.1	11,000	87,200	31,300	0.16
			3	8	52	15	6.2	8,900	100,300	33,500	0.17
50,000	2000	20	3	8	52	15	6.6	33,400	104,600	59,000	0.30
100,000	500	10	2	8	36	15	10.7	22,000	155,900	58,500	0.15
			2	16	52	15	8.6	22,000	150,700	57,300	0.14
150,000	500	10	2	16	52	15	11.0	33,000	214,100	83,100	0.14

*Based on 4000 hours of operation per year and equipment depreciated 13% a year using the straight-line depreciation method.

Table 11-4

OPTIMUM DESIGN OF SPRAY SCRUBBERS†

Flow, cfm	Average odor units Inlet	Average odor units Outlet	Number of stages	Chamber length, ft	Scrubber height and width, ft	GPM/nozzle	Liquid rate per stage, gpm	$/1000-cfm-hr*
25,000	500	10	2	8	4.8	3.0	414	0.17
25,000	2000	20	3	8	4.4	3.0	352	0.31
50,000	500	10	2	8	7.1	2.5	764	0.16
50,000	2000	20	3	8	6.6	2.5	648	0.30
100,000	500	10	2	16	8.6	3.0	1320	0.14
150,000	500	10	2	16	11.0	2.5	1820	0.14

---

†Optimum combination selected based upon annual rate of return on incremental capital expenditure for additional stages. For example,

$$\text{Annual rate of return for 3 stages instead of 2 stages} = \frac{\Delta(\text{Operating costs, 2-3})}{\Delta(\text{Capital expenditure, 3-2})}$$

Assumed a minimum annual rate of return of 10% required for additional stages.

*Based on 4000 hours of operation per year and equipment depreciated 13% a year using the straight-line depreciation method.

towers require over twice the capital investment of horizontal spray towers. Thus, for plant ventilating air (odor levels less than 2,000 odor units), spray scrubbers are recommended. Packed towers should be restricted to small-volume high-intensity streams where a large reduction (greater than 90%) in odor level is required.

12. DESIGN AND COST OF A PACKED TOWER-HORIZONTAL SPRAY SCRUBBER SYSTEM

It was concluded from the information presented in the previous sections, that both packed towers and spray scrubbers can be designed to obtain specified odor reductions. If process air and plant ventilating air are both to be treated by wet-scrubbing, what is the most economical design? Spray scrubbers require less capital investment to obtain the same removals for large gas volumes; however, should one large spray scrubber be designed to treat both sources, or should the process air first be treated with a packed tower, and then sent to the ventilating air scrubber? To evaluate these alternatives, an economic determination of the two different systems was performed.

Figures 12-1 and 12-2 depict the two designs considered for a rendering plant with a 10,000 cfm high intensity gas stream (8,000 odor units) and 90,000 cfm of ventilating air (500 odor units). Both scrubber systems were designed to achieve a maximum outlet odor level of 100 odor units. The continuous blow-down and make-up scheme was used in both systems to reduce chemical costs*. Required removal efficiencies varied in each design. In Case I, the three-stage horizontal spray scrubber was required to achieve a 99% reduction of the odorants, while in Case II, the packed tower needed only an 87.5% removal, with the spray tower removing 98%.

The costs associated with each design are presented in Table 12-1. Pre-treatment of the concentrated odor stream in a packed tower proves to be more economical than use of one spray scrubber to handle the entire load. The primary saving is the $4,500 per year power costs. The capital expenditure is also lower for Case II by $8,300, while the

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*Note that in existing installations similar to Case II the packed-bed scrubber has its own chemical supply system, increasing the chemicals cost.

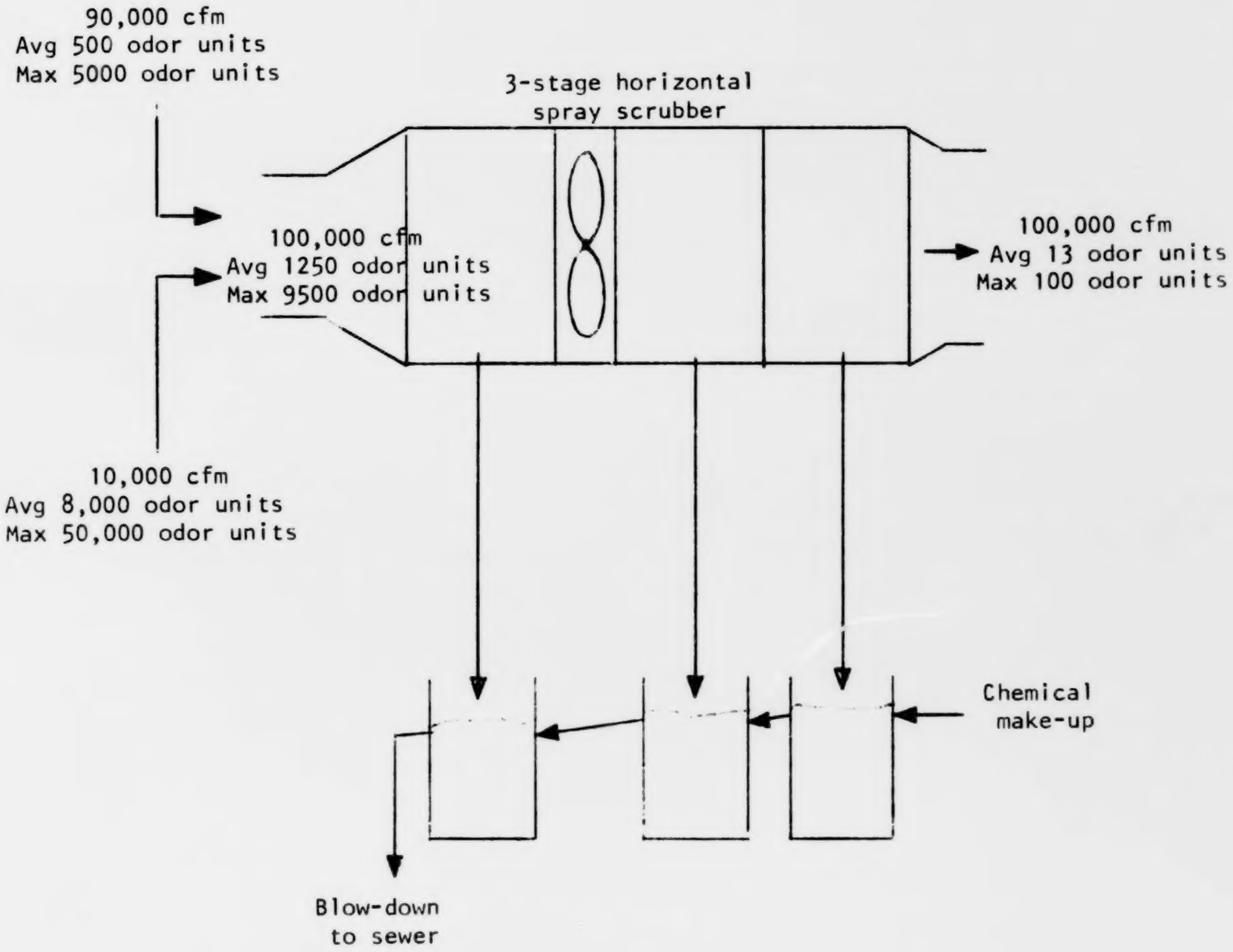

90,000 cfm
Avg 500 odor units
Max 5000 odor units
3-stage horizontal spray scrubber
100,000 cfm
Avg 1250 odor units
Max 9500 odor units
100,000 cfm
Avg 13 odor units
Max 100 odor units
10,000 cfm
Avg 8,000 odor units
Max 50,000 odor units
Chemical make-up
Blow-down to sewer

Figure 12-1

CASE I - 3-STAGE SPRAY SCRUBBER

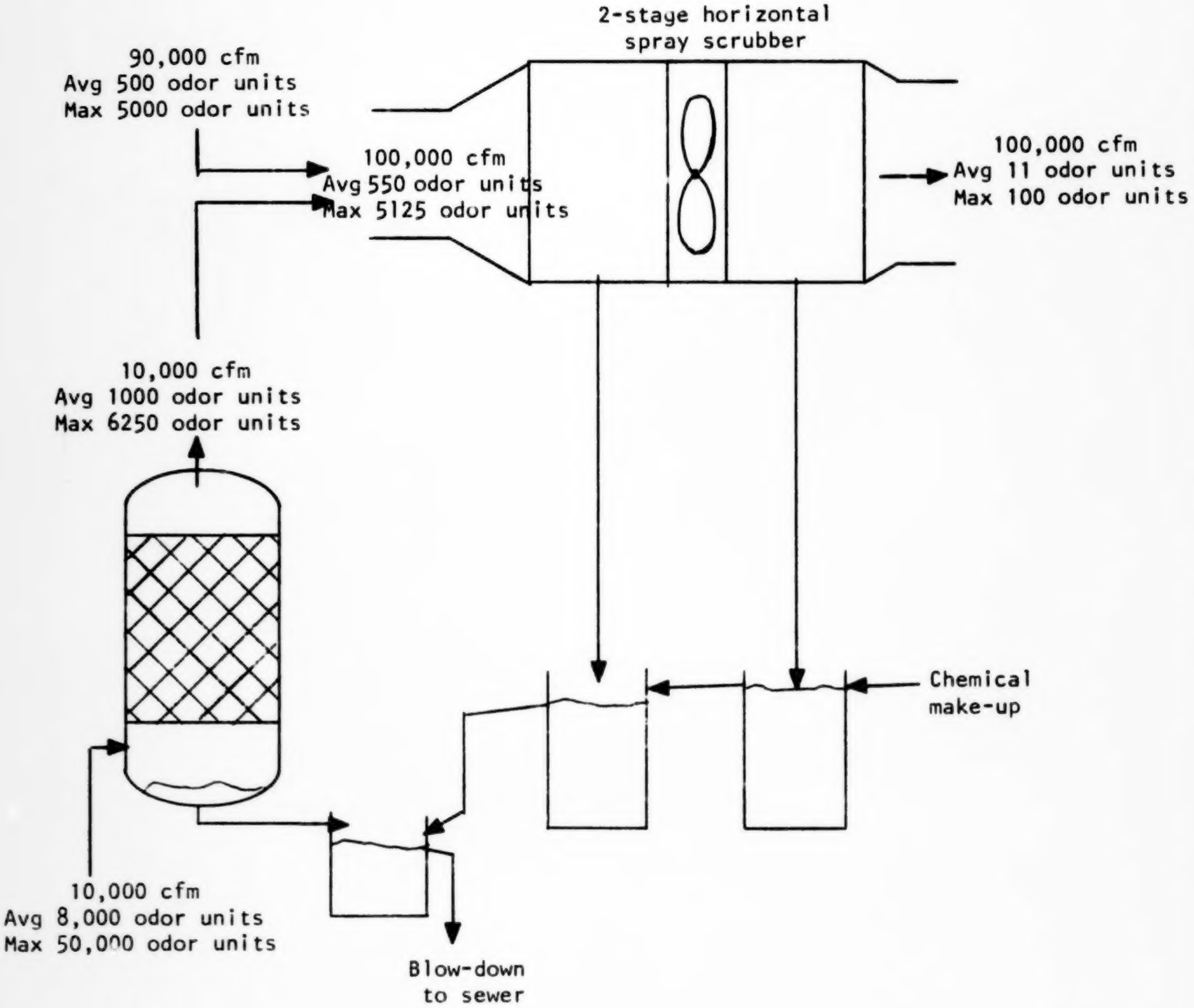

2-stage horizontal spray scrubber
90,000 cfm
Avg 500 odor units
Max 5000 odor units
100,000 cfm
Avg 550 odor units
Max 5125 odor units
100,000 cfm
Avg 11 odor units
Max 100 odor units
10,000 cfm
Avg 1000 odor units
Max 6250 odor units
Chemical make-up
10,000 cfm
Avg 8,000 odor units
Max 50,000 odor units
Blow-down to sewer

Figure 12-2

PACKED-BED WITH A 2-STAGE SPRAY SCRUBBER

Table 12-1

COMPARISON OF SCRUBBING SYSTEMS

	Case I 3-stage spray scrubber	Case II 2-stage spray scrubber and 1-stage packed tower
Spray Scrubber Design		
Chamber length, ft	8	16
Height and width, ft	9.9	8.6
Total length, ft	52	52
Liquid flow rate, gpm/stage	1,174	1,316
Packed Tower Design		
Tower diameter, ft		7.9
Packing depth, ft		8.6
Liquid flow rate, gpm		690
Costs		
Capital investment, $		
Spray scrubber	183,100	148,500
Packed tower	-	26,300
Total	183,100	174,800
Chemical cost, $/yr	42,600	42,600
Power, $/yr	17,500	13,000
Maintenance, $/yr	4,400	4,400
$/1000 cfm-hr	0.221	0.207

project maintenance and chemical costs for both systems are equal.

The use of the packed tower for treating process air streams increases the reliability of the system. The technology for reducing high intensity odors by at least 87% in a single-stage packed tower was consistently demonstrated throughout this program. The discharge from the packed bed only increases the average odor intensity to the ventilating scrubber from 500 to 550 odor units. Thus, the spray scrubber is still treating a dilute gas stream very similar to just ventilating air, which is the most advantageous application of spray scrubbers.

13. ACTIVATED CARBON STUDY

Although the emphasis of this project focused on developing wet scrubber systems for odor control, a small study on the effectiveness of activated carbon was also performed. This study measured the performance of a carbon system and was used to determine the adsorptive capacity of the carbon using actual rendering plant air.

13.1 Laboratory Carbon Test

A three-stage carbon adsorber was constructed by the Calgon Corporation for this test. Each stage in the adsorber contained 540 gm of carbon. The adsorber was connected in parallel with the laboratory scrubber so both could be utilized to treat the concentrated odor stream normally sent to the incinerator. A flow of 17 cfm was passed through the adsorber for a period of 20 hr. Bag samples were collected on the inlet and outlet at 2 hr, 10 hr and 20 hr. Gas chromatograph samplers were also used for the 20-hr sample on both the inlet and outlet.

The odor removal results are presented in Tables 13-1 and 13-2. The data show that carbon was very effective in deodorizing the gas for the first 10 hr; however, by the 20th hour the odor removal had dropped off to 54%, indicating that the carbon was becoming saturated. The gas chromatograph results tabulated in Table 13-2 indicate an unusual pattern. The lighter molecular weight compounds were still being effectively removed after 20 hours, while the heavier compounds appeared to be passing through the carbon. This is extraordinary since in carbon applications involving a homologous series, the lighter molecular weight compounds are the first to break through. The heavier compounds begin to replace the lighter compounds in the bed forcing the lighter compounds to pass through the bed more quickly. These experimental results indicate that carbon has a high adsorption affinity for the

Table 13-1

ACTIVATED CARBON - ODOR PANEL RESULTS

Time, hr	Odor levels		Odor panel % removal	GC % removal
	Inlet	Outlet		
2	2750	45	98.4	-
10	1700	50	97	-
20	4800	2200	54	74

particular lighter odorous compounds found in rendering plant air. Three of the five lighter compounds contain sulfur, and carbon has a high adsorptive capacity for many sulfur compounds. This may explain the apparent affinity of carbon for these compounds.

After the 20-hr test was completed, the carbon was removed from each stage, dried, and weighed. The following results were obtained:

	% increase in weight
1st stage	29
2nd stage	20
3rd stage	16

These results demonstrate that the adsorption capacity for rendering plant process air odors is greater than the 10% weight adsorption capacity typically used for designing carbon adsorbers. The large quantity of organics adsorbed per pound of carbon was at least in part due to the high inlet odor concentration in this experiment. Some caution should be used if the results are applied to plant ventilating air, which contains lower odor concentrations. An adsorptive capacity of 5-10 wt% rather than 29 wt% would be a safer assumption for plant ventilating air, because as the inlet concentration decreases, the adsorptive capacity also decreases.

Table 13-2

ACTIVATED CARBON TEST
TIME: 20 HOURS

	Inlet	Outlet	% removal
Odor ED_{50}	4800	2200	54
GLC peaks, μg/liter air			
1. Dimethyl sulfide	22.10	0.53	98
2. Pungent U.P. 90	15.37	0.17	98.9
3. Dimethyl disulfide	7.38	0.09	98.8
4. Butyric acid	0.83	0.41	51
5. Propylene sulfide (cabbage 880)	1.11	0.14	87
6. Bitter 655	36.99	0.27	99.3
7. Burnt 1233A (pyrazine)	-	-	-
8. Burnt 1233B (pyrazine B)	1.54	0.55	64
9. Rendering 1335	80.01	32.37	60
10. Fatty 1545	9.84	2.93	70
11. Burnt 1687 (quinoline)	2.86	1.13	60
12. Sulfur 660	-	-	-
13. Cheesy 2002	2.78	1.45	48
14. Unpleasant 2582	1.09	0.58	47
15. Fatty acid 1980	4.67	0.88	81
16. Fatty acid 2160	5.09	1.54	70
Average percent removal of each component			74

There is certainly a need for additional research on this subject before the economics of activated carbon can be developed as thoroughly as those of wet scrubbing; however, the results from this one test are very encouraging. Not only does the adsorption capacity of carbon at low odor levels need to be determined, but also the effect of regeneration on the adsorption capacity.

13.2 Regeneration of Activated Carbon

The economics of carbon adsorption depends on the method of regeneration, and the degree of regeneration that is possible. Some loss in adsorptive capacity often occurs with each regeneration cycle. Only by experimentally repeating the adsorption-regeneration cycle many times can the rate of deterioration of the carbon be accurately estimated.

Several methods of regenerating carbon are available. Regeneration by passing hot gases through the bed to drive off the adsorbed material requires an incinerator to deodorize the hot gases. This method is costly for rendering plants (Report No. EPA-R2-72-088, p. 32). Where available, regional regeneration plants operated by the carbon manufacturers would probably be the most economical method. One other method that could also prove very economical, if successful, would be in-situ chemical regeneration. The capital investment would be minimal, and if the carbon could be chemically regenerated anywhere near its original capacity, the economics would be greatly improved. Perhaps a solution containing the hypochlorite ion, either a high pH or low pH solution would be very effective. Until more work in this area is performed, the cost of activated carbon for odor control can only be estimated on a throw-away basis, and this is done in the next section.

13.3 Estimated Cost of a Carbon System Without Regeneration

For low odor intensity levels (less than 100 odor units), the economics of using carbon on a throw-away basis have been estimated. One potential use of carbon is on the outlet of a scrubber to achieve odor levels of 10-20 odor units at all times. A carbon bed 2-3 in. thick could be placed after the final demister for a minimal cost and with a small increase in the over-all pressure drop. From the results obtained from this test, the carbon adsorbed 0.773 lb of organics for the 24-hr test. Assuming an average odor reduction of 3000 odor units during the 20-hr test, the total quantity of odorants removed was

$$\text{Odorants removed} = \begin{array}{c|c|c|c} \text{3000 odor units} & 17\ \text{ft}^3 & 60\ \text{min} & 20\ \text{hr} \\ \hline & \text{min} & \text{hr} & \end{array}$$

$$= 61 \times 10^6\ \text{odor-units-ft}^3$$

Thus, 61×10^6 odor-units-ft^3 must be equivalent to the quantity of organics adsorbed by the carbon, 0.773 pounds, or

$$80 \times 10^6\ \text{odor units-ft}^3 = 1\ \text{lb organics}$$

Using this number, the annual cost of carbon as a polishing step was estimated for several conditions. Because of the lower inlet odor levels, adsorption capacities of 5 and 10% were used. The results are presented in Table 13-3. The cost of the carbon is obviously directly proportional to the gas flow rate and odor reduction. At the higher gas flow rates, carbon costs are too high to be economically considered on a throw-away basis. Even at 10,000 cfm, the annual replacement cost of the carbon will range between $4,200 and $8,400, depending on the true adsorption capacity. The costs presented do not include the capital expenditure or labor cost.

Using carbon on a throw-away basis does not appear to be economically atractive, even for low-intensity odors (less than 100 odor units). More research is needed to determine how the carbon can be economically regenerated.

Table 13-3

COST OF ACTIVATED CARBON FOR LOW ODOR LEVELS

Flow, cfm	Average odor levels		Annual carbon cost ($/yr)*	
	Inlet	Outlet	5% capacity	10% capacity
10,000	50	10	8,400	4,200
	100	20	16,800	8,400
25,000	50	10	21,000	10,500
50,000	50	10	42,000	21,000
100,000	50	10	84,000	42,000
	100	20	168,000	84,000

*Carbon cost of $0.35/lb, no regeneration, carbon bed operated 4000 hr/yr.

14. ON-SITE GENERATION OF SODIUM HYPOCHLORITE

Rendering plants that are currently using sodium hypochlorite, typically purchase chlorine gas and bubble the gas into a caustic solution to produce sodium hypochlorite. This method, although the most economical, has several disadvantages. Today there is a shortage in the United States of both chlorine gas and sodium hypochlorite. In addition, storage of chlorine gas presents a safety problem. Many cities have banned the storage of bulk quantities of chlorine gas within the city limits, thus forcing users to purchase sodium hypochlorite in solution form.

Purchased in one-ton cylinders, chlorine gas currently sells for $0.11/lb delivered. The price depends on location, and may vary from less than $0.11 to greater than $0.20/lb. In tank-car quantities, chlorine gas can be purchased for $0.06 to $0.07/lb. The large difference in price is due to the handling and delivery charges.

When a plant switches to purchased sodium hypochlorite solution for safety reasons, there is an even more severe economic penalty. Purchased sodium hypochlorite typically sells for $0.28/lb equivalent chlorine in 5,000-gal shipments. The price of sodium hypochlorite also varies with geographic location.

Delivered caustic soda currently sells for $0.085/lb, but again delivery costs will determine the actual price. The cost in 55-gal drums of 50% caustic solution is higher than the cost of caustic solution in bulk. It will pay the larger rendering plants to provide an indoor storage tank and purchase caustic solution in tank-truck quantities. The tank must be protected from cold weather to prevent crystallization from occurring.

Because of the safety problems and the shortage of chlorine gas, an alternative was evaluated. Several firms have developed packaged units for on-site generation of sodium hypochlorite solution. On-site generation units utilize salt water for the feed material. The salt water is pumped through electrolytic cells, where an electric current is passed through the water, producing a dilute NaOCl solution.

The economics of on-site generation depend upon the costs of chlorine, electricity, and salt. Table 14-1 presents the costs associated with on-site generation as compared to purchasing chlorine gas and sodium hypochlorite. On-site generation can provide savings to plants currently purchasing sodium hypochlorite. For plants purchasing chlorine gas at or below \$0.11/lb, on-site generation is not economically competitive.

The capital investment in an on-site generation is considerable, ranging up to \$94,000 for a 50,000-cfm scrubber treating an average odor intensity of 3,000 odor units. In Table 14-1, the total cost-per-year values were computed assuming a 15-year equipment life and a 10% interest rate, and that the maintenance cost is negligible. Thus, the total cost-per-year column can be compared directly with the "purchased chemical cost" columns because the time value of money is taken into account. For the last example presented in Table 14-1, on-site generation costs only \$1,100 per year more than purchasing chlorine. If the price of chlorine increases to \$0.12/lb, on-site generation will become economically competitive. Of course, a guaranteed long-term supply of cheap electricity or salt would also improve the competitive position of on-site generation. Each installation should evaluate on-site generation using the anticipated chemical and electrical costs. Larger installations will find on-site generation more attractive.

On-site generation units are typically limited to production of 0.6 to 0.8 wt% hypochlorite solution. On-site generator

Table 14-1

ON-SITE GENERATION OF SODIUM HYPOCHLORITE

Flow, cfm	Average odor units		Number of stages	Purchased chemical cost		On-site generation			Annual savings of on-site generation over purchased NaOCl, $
	Inlet	Outlet		Cl_2 + NaOH $/yr(2)	NaOCl + NaOH $/yr(2)	Capital investment, $	Operating cost, $/yr(1)	Total cost per year(3)	
5,000	8000	40	3	13,100	17,300	40,000	10,500	15,700	1,600
10,000	8000	20	3	26,300	34,700	71,000	19,600	28,800	5,900
25,000	500	10	1	9,000	11,500	32,000	7,700	11,900	-
25,000	2000	20	2	20,200	26,500	55,000	15,400	22,600	3,900
50,000	2000	20	2	40,400	53,000	94,000	29,300	41,500	11,500

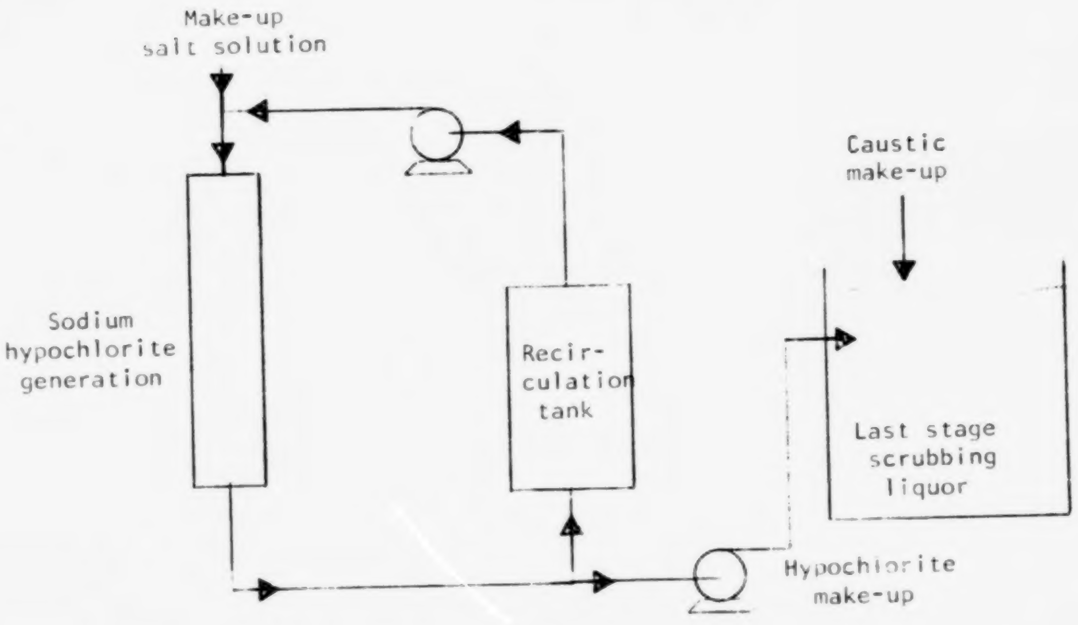
[1] Includes 3.5 lb of salt and 2.5 KWH/lb of chlorine; operating cost does not include depreciation.

[2] Unit costs, Cl_2 - $0.11/lb
NaOH - $0.085/lb
NaOCl - $0.28/lb
Salt (NaCl) - $0.015/lb
Electricity - $0.025/KWH.

[3] Operating cost plus depreciation cost (13% of capital investment).

units require very little space, are easy to operate, and require minimal operator attention. Most of the units available commercially have a modular design, so that if more hypochlorite is required in the future, another module can be added without costly modifications. Only about 30% of the salt solution is converted to the sodium hypochlorite; thus, the scrubbing solution will also contain high levels of dissolved solids. Sewer ordinances for dissolved solids must be checked to insure that on-site generation will not create an effluent violation.

In order to obtain sufficient concentration of the hypochlorite ion, the brine solution must be recirculated through the generator. Ideally, the scrubbing solution used in the last stage could be recycled through the generator; however, this may result in fouling and the high pH affects the performance of some of the commercial generators. Thus, unless a guarantee from the vendor can be obtained, it is recommended that a separate tank be installed for recirculating the solution, as shown below.


Make-up
salt solution
Caustic
make-up
Sodium
hypochlorite
generation
Recir-
culation
tank
Last stage
scrubbing
liquor
Hypochlorite
make-up

In commercially available hypochlorite generators, hypochlorite solution is produced by electrolysis of sodium chloride solution. Chlorine is generated at the anode:

$$2Cl^- \rightarrow Cl_2(\text{dissolved}) + 2e^-$$

and hydroxyl ion at the cathode:

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2(\text{gas})$$

The chlorine and hydroxyl ion combine in solution:

$$Cl_2 + 2OH^- \rightarrow OCl^- + Cl^- + H_2O$$

producing one molecule of hypochlorite ion (OCl^-), and reforming one chloride ion (Cl^-). The overall reaction is:

$$NaCl + H_2O \xrightarrow[2e^-]{} NaOCl + H_2\uparrow$$

Note that this is the equivalent of adding chlorine gas and caustic soda to the solution. If a pH of 11 or 12 is wanted, then additional caustic must also be added to the product from the electrolyzer.

In conclusion, on-site generation provides an economic alternative to rendering plants currently purchasing sodium hypochlorite. On-site generation is also attractive where shortages of chlorine gas exist, where safety standards are forcing plants to switch from chlorine gas, and where the cost of chlorine gas is greater than the $0.11/lb assumed in this report. If the price of chlorine increases in the next few years, on-site generation may find wide-spread acceptance throughout the rendering industry.

15. SELECTING THE PROPER SCRUBBER DESIGN

In this chapter a comparison of packed beds and spray scrubbers is provided. Some of the more practical design problems associated with scrubbers are also discussed. Although the scope of the project was limited to these two types of scrubbers, much of the information obtained during this project can be extended to other types of scrubbing systems.

15.1 Comparison of Packed Bed and Spray Scrubbers

In Chapter 10, cost information is provided for packed-bed scrubbers operating at low gas volumes (5,000-10,000 cfm) with process air, and also at higher gas volumes (25,000-50,000 cfm) with plant ventilating air. Cost information for spray scrubbers is presented in Chapter 11 for gas throughputs greater than 25,000 cfm. No spray scrubber cost information is provided at the lower gas throughputs with higher odor levels because packed towers are more economic in this range.

The main difference in the costs of the two types of scrubbers is the difference in capital cost. Table 15-1 is a comparison of the two scrubber types at moderate gas flows and odor levels. It is apparent from Table 15-1 that the capital investment for packed-bed scrubbers is approximately twice that for a spray scrubber system. The electrical power cost of spray scrubbers is also lower than packed bed scrubbers if low-pressure nozzles (15 psig) are used. The available space for a scrubbing system will also influence the cost considerations and ultimate selection. Packed-bed scrubbers can be placed inside a building or outdoors. Spray scrubbers can be placed on a roof with minimal additional structural support or can be built inside a plant. Based on total over-all cost, spray scrubbers are more economical for volumetric gas throughputs greater than 25,000 cfm.

Table 15-1

COSTS OF PACKED BED VERSUS SPRAY SCRUBBERS FOR PLANT VENTILATING AIR

Operating conditions			Packed bed scrubber				Spray scrubber			
	Average odor units									
Flow, cfm	Inlet	Outlet	Number of stages	Capital investment, $	Power cost, $/yr	$/1000 cfm-hr(1)	Number of stages	Capital investment, $	Power cost, $	$/1000 cfm-hr(1)
25,000	500	10	2	96,100	4,360	0.24	2	49,800	3,290	0.17
25,000	2000	20	3	120,800	5,860	0.40	3	60,100	4,540	0.31
50,000	500	10	2	181,400	8,910	0.23	2	87,200	6,460	0.16
50,000	2000	20	3	230,300	11,730	0.39	3	104,600	8,900	0.30

[1] Based on 4000 hours operation per year and equipment depreciated 13% per year.

In Chapter 12, a total scrubbing system was presented for treating rendering plant odors. The high-intensity odors are more economically treated by a small packed-bed scrubber followed by a large plant spray scrubber, than by sending the high intensity odors directly to the ventilating air spray scrubber. The major cost savings of the dual scrubber system are in the capital investment and in the power cost.

15.2 Use of Venturi Scrubbers

Several rendering plants have installed venturi scrubbers prior to packed-bed scrubbers to treat cooker noncondensibles. The purpose is not to remove gaseous odors, but to remove particulates. In this project, we attempted to determine whether particulate matter is an important source of odors. The experiments described in Chapter 5 indicated that particulates were not an important source of odor in plant ventilating air. In spite of this finding, venturi scrubbers might still be needed as a pretreatment step before packed bed scrubbers, to prevent entrained grease particles from fouling the packing. In our laboratory scrubber experiments at Des Moines, we observed no particulate deposits on the packing even when scrubbing high-intensity air that normally goes to an incinerator; but we did observe some deposits of grease in a 200-ft line that connected our scrubber with the air source.

Prokop (1974) reported that 5 lb/min of particulates were removed from the off-gases from a poultry feather dryer. Such a loading would rapidly foul a packed-bed scrubber.

We suspect that the need for a venturi scrubber depends on the type of condenser used. A direct-contact (barometric) condenser will remove much of the greasy particulates from the condenser off-gases. Mill, et al. (1963) reported that a direct-contact condenser removed 99% of the odor from cooker off-gases. An indirect (tube-and-shell) condenser was reported to remove 50% of the odor, and it will probably remove less of the particulates. On the other hand, the indirect condenser allows the grease removed to be recycled to the process, whereas the direct condenser results in a larger effluent stream that may cause a wastewater disposal problem.

The venturi scrubber acts as a second condenser of the direct-contact type. Plain water is usually used for the venturi scrubbing solution, and it is sent directly to the drain, just as in a direct-contact condenser. Thus, a venturi scrubber may be needed as a pretreatment before a packed-bed scrubber for process air, only if the plant does not have a direct-contact condenser. The decision should be based on tests of particulate level at the individual plant. The cost of the venturi scrubber will not be excessive if it treats only the noncondensibles from the cooker, which usually amounts to only a few hundred cfm.

Another reason for using a venturi scrubber might be to further lower the temperature of the gas to a packed-bed scrubber. Tests reported elsewhere in this report indicate the holding capacity of scrubber solutions may be reduced when the temperature of the solution increases. Any type of spray scrubber could provide precooling with once-through water.

15.3 Design Odor Levels

The design of pollution control equipment must be based on achieving acceptable emission quality during the periods of maximum loading. During our tests at Des Moines, we found that the air odor levels varied by a factor of 100, and sometimes by a factor of 10 within a period of an hour.

Target emission odor levels depend on the dispersion characteristics of the plant environs, and the distance to neighbors. These matters are discussed in a recent EPA Report (Osag, et al., 1974). For example, if a plant is located one mile from its nearest neighbors, an emission of 25,000 cfm at 100 to 200 odor units will be diluted by atmospheric dispersion to acceptable levels. The atmospheric dispersion can be aided under most weather conditions if the scrubber air is emitted from a stack 50 ft high. The use of a stack without a scrubber will not eliminate odor problems during periods of adverse meteorological conditions. For larger emissions (100,000-150,000 cfm), odor levels lower than 100 odor units may be necessary, especially where the plant is located very close to a residential or light business area.

The design models presented in Chapters 10 and 11 are based on the measured odor levels at the Des Moines rendering plant. The cooker off-gas after the condenser averaged 8,000 odor units during the tests performed, but the maximum odor level was slightly greater than 50,000 odor units. The plant ventilating air averaged 500 odor units, with a maximum level of 5,000 odor units. Every plant will have different odor levels, depending upon how many of the high odor intensity sources are collected and treated separately from the ventilating air.

15.4 Corrosion Resistance

The use of sodium hypochlorite in an alkaline solution as the scrubbing liquid requires that the materials of construction be selected very carefully. (This is also true of some of the scrubbing liquids tried by certain plants such as chlorine water.) It is known that stainless steels are subject to pitting corrosion with solutions that contain chlorides. Fiberglass-reinforced plastic (FRP) is recommended for the liquid storage tanks and the packed-bed scrubbers. Vinyl esters are generally recommended by suppliers as the material from which FRP should be made for exposure to NaOCl solutions. Fabrication of all FRP structures should conform with the proposed Product Standard for Custom Fabricated Reinforced Polyester Corrosion Resistant Process Equipment TS-5687. In particular, they should be designed with adequate strength in case the entire tower is flooded with the scrubbing liquid. Manufacturers of FRP tanks should be familiar with these proposed standards.

PVC has generally been used for process piping for rendering plant scrubbers. No corrosion problems have been reported, but failure due to vibration has been known to occur.

The horizontal spray scrubber at the Des Moines plant is one of 30 installations of this type. Part of the scrubber is type 304 stainless steel, while part of the scrubber is type 316 stainless steel. An aluminum fan is used after the first stage. The use of sodium hypochlorite, with excess caustic in these units will reduce the expected equipment life because of high corrosion rates.

Any entrainment from the first stage onto the aluminum fan will result in excessive corrosion rates. Rabald (1968) reported that even dilute concentrations of caustic and/or hypochlorite results in high corrosion rates of aluminum. The problem has been solved by custom-coating the fan with vinyl ester resin.

Caustic presents no problem to stainless steel; however, severe pitting of type 304 stainless steel will occur when subjected to sodium hypochlorite solutions. Type 316 stainless steel is also subject to pitting, but not nearly to the extent of type 304. For many situations where sodium hypochlorite solutions are used, type 316 will be suitable (Mellan, 1966). The pitting rate will be a function of the hypochlorite concentration, the pH, and other chemicals present in the water.

No quantitative information could be found in the literature concerning the effect of hypochlorite concentration and the pH on corrosion rates. A representative of a chlorine company (S.P.D. Services, Forest Park, Illinois) was contacted to ascertain if they had had any experience in this area. Although they had no published data, it has been their experience that the corrosion rates increase as the hypochlorite level increases for both type 304 and 316 stainless steel. This firm felt that the alkaline pH reduced the corrosion rates and that at concentrations from 0.03 to 0.1% hypochlorite the pitting problems would be minimal for type 316 stainless steel.

In the recommended continuous blow-down system, the hypochlorite level is maintained above 0.1%; thus, neither type 304 nor 316 stainless steel is suitable for constructing new scrubbers. Serious consideration should be given to the construction of horizontal spray scrubbers of fiberglass reinforced plastic (FRP). Process Equipment Corporation (1974) estimated that the total cost of FRP construction for horizontal scrubbers would be slightly less than constructing the scrubbers of type 304 stainless steel. The expected life of the scrubber would be extended significantly with the FRP because of the reduced corrosion rates.

For existing stainless steel scrubber installations, a plastic coating can be sprayed on the inside of the scrubber to protect the steel from the liquid solutions. The cost of spraying a 100,000 cfm, three-stage scrubber is approximately $10,000 for the complete job. The aluminum fan can be spray-coated with the same material. Before coating, the metal must be thoroughly sand-blasted to prepare the surface. The recommended coating thickness is 35 to 40 mils, and this results in a coating that is both mechanically and chemically resistant. Coatings recommended by manufacturers for alkaline hypochlorite solutions are vinyl ester containing glass flake filler, or polyester containing similar filler. It is standard practice to spark-test the coatings to insure that there are no pin-holes. Scrubbers that have already developed leaks can be coated, since the leaks are usually from pinholes, and the metal is still sound.

Existing scrubbers that have not been coated can be operated with sodium hydroxide scrubbing solutions at pH > 12. Although this liquid is not as effective as hypochlorite, test data in this report indicate it is effective against most odorants. Low concentration hypochlorite may be used in a type 316 stainless scrubber section, although quantitative corrosion data are not available. In such cases, sodium silicate has been suggested as a corrosion inhibitor, although data are not available. Uncoated aluminum fans must not be subjected to mist from either alkaline or acid solutions.

15.5 Specifying the Auxiliary Equipment

When designing a scrubber system, careful attention should be paid to the following matters:

- Liquid Pumps

  Pumps should be properly sized to deliver the specified amount at the specified head loss. Over-design of pumps leads to throttling the discharge valve to obtain the proper rate.

  Throttling the discharge valve results in an increase in head loss and the consumption of excess electricity.

- Minimizing the Liquid Head Loss

  When scrubbers are placed on the roof of a building and the liquid tanks are placed on the floor inside the building, the pumps must lift the liquid in excess of 30 ft. When the liquid pumping rate is high, which is the case with large scrubbers, the annual power costs can be considerable. The system should be designed to minimize the height difference from the top of the liquid tank and the scrubber nozzles to reduce the pump horsepower, and thus the annual power cost.

- Liquid Drainage from Tower

  The return line from the tower to the liquid holding tank must be properly sized to prevent the liquid from building up in the tower. When the liquid accumulates in a tower, the liquid pumping rate must be reduced and the scrubber efficiency decreases. Of course, the use of larger nozzles than intended can overtax the return line capacity.

- pH Control

  Because of the importance of maintaining the pH in the last stage at pH 12, automatic pH control should be included in each plant.

15.6 Water Pollution Implications

The use of sodium hypochlorite scrubbing solutions with an alkaline pH does not present any serious water pollution problems. Any sodium hypochlorite discharged to the sewer will continue to oxidize organics in the wastewater. (Prechlorinating in the pumping stations and in the primary sedimentation basins is common practice in municipal wastewater treatment plants to inhibit the production of H_2S, to prevent corrosion and septic odors in the sewerage system.)

The alkaline pH will not present any problems if a continuous blow-down approach is utilized. However, if a batch system is utilized, and the tanks are rapidly discharged to the sewer, any grease in the sewer will be emulsified. Emulsified grease will not be removed through the grease collection system. Thus, alkaline solutions (pH 11-12) must be neutralized prior to discharging if the tanks are rapidly dumped.

15.7 Summary

Based on the information provided in this report, a rendering plant should be able to estimate the cost of a scrubber system. The accuracy of preliminary cost estimates based on general equations such as are presented in this report is usually ±30%. The cost information can be used to select the optimum equipment design, but the final cost will be determined by obtaining bids for the chosen scrubber.

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APPENDIX 1

COMPARATIVE SCRUBBING TEST RESULTS

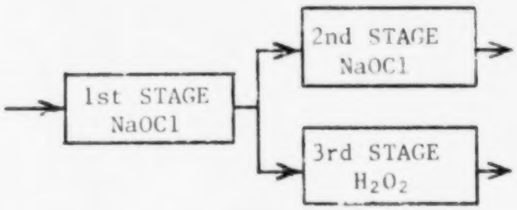

Table A-1

RESULTS OF SCRUBBING TEST 31-1
LABORATORY SCRUBBER, TIME: 1/2 HOUR

	Inlet	Outlet from #2 (NaOCl)	Outlet from #3 (H_2O_2)	1 → 2 % Removal	1 → 3 % Removal
Odor ED_{50}	700	25	265	96	62
GLC peaks, μg/liter air					
1. Dimethyl sulfide	79.34	4.47	14.48	94	82
2. Pungent U.P. 90	21.41	0.47	4.60	98	79
3. Dimethyl disulfide	1.43	0.04	0.38	97	73
4. Butyric acid	7.65	0.65	1.20	92	84
5. Propylene sulfide (cabbage 880)	4.09	0.21	0.58	95	86
6. Bitter 655	37.40	0.93	11.40	98	70
7. Burnt 1233A (pyrazine)	2.98	0.10	0.90	97	70
8. Burnt 1233B (pyrazine B)	6.30	0.90	2.30	86	63
9. Rendering 1335	214.0	15.91	32.70	93	85
10. Fatty 1545	67.84	4.27	4.47	94	93
11. Burnt 1687 (quinoline)	23.48	1.00	10.52	96	55
12. Sulfur 660	-	-	-	-	-
13. Cheesy 2002	34.70	2.13	6.23	94	82
14. Unpleasant 2582	12.43	1.03	1.97	92	84
15. Fatty acid 1980	10.26	0.61	1.56	94	85
16. Fatty acid 2160	9.94	0.50	0.88	95	91
Average percent removal of each component				94	79

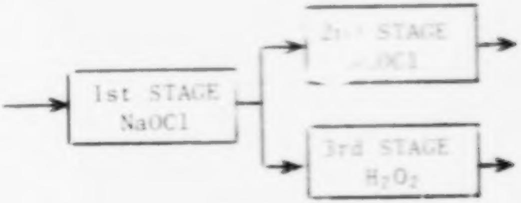

Table A-2

RESULTS OF SCRUBBING TEST 31-2
LABORATORY SCRUBBER, TIME: 1-1/2 HOURS

	Inlet	Outlet from #2 (NaOCl)	Outlet from #3 (H_2O_2)	1 → 2 % Removal	1 → 3 % Removal
Odor ED_{50}:	-	-	-	-	-
GLC peaks, ug/liter air					
1. Dimethyl sulfide	93.55	9.53	3.13	90	97
2. Pungent U.P. 90	18.62	0.65	2.03	97	89
3. Dimethyl disulfide	3.22	0.77	0.19	76	94
4. Butyric acid	23.33	3.37	0.24	86	99.0
5. Propylene sulfide (cabbage 880)	7.14	0.75	0.03	89	99.6
6. Bitter 655	25.72	3.25	6.17	87	76
7. Burnt 1233A (pyrazine)	4.50	1.29	0.26	71	94
8. Burnt 1233B (pyrazine B)	14.67	-	0.29	-	-
9. Rendering 1335	345.43	31.62	11.05	91	97
10. Fatty 1545	114.64	11.75	2.40	90	98
11. Burnt 1687 (quinoline)	78.20	14.11	0.53	82	99.3
12. Sulfur 660	-	-	-	-	-
13. Cheesy 2002	71.93	14.65	0.83	80	98.8
14. Unpleasant 2582	35.12	7.45	0.28	79	99.2
15. Fatty acid 1980	9.12	0.92	0.26	90	97
16. Fatty acid 2160	30.10	3.19	0.35	89	98.8
Average percent removal of each component				86	95

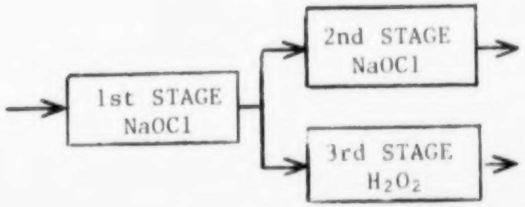

Table A-3

RESULTS OF SCRUBBING TEST 31-3
LABORATORY SCRUBBER, TIME: 3 HOURS

	Inlet	Outlet from #2 (NaOCl)	Outlet from #3 (H_2O_2)	1 → 2 % Removal	1 → 3 % Removal
Odor ED_{50}	15,500	45	370	99.7	98
GLC peaks, µg/liter air					
1. Dimethyl sulfide	48.93	21.29	11.67	56	76
2. Pungent U.P. 90	14.02	2.25	6.14	84	56
3. Dimethyl disulfide	2.88	0.15	0.39	95	86
4. Butyric acid	3.75	1.39	0.71	63	81
5. Propylene sulfide (cabbage 880)	2.15	0.39	0.39	82	82
6. Bitter 655	28.63	2.97	7.78	90	73
7. Burnt 1233A (pyrazine)	1.75	2.07	0.59	-	-
8. Burnt 1233B (pyrazine B)	7.88	-	2.65	-	-
9. Rendering 1335	150.55	33.47	23.22	78	84
10. Fatty 1545	25.16	10.59	6.25	58	75
11. Burnt 1687 (quinoline)	15.70	-	4.63	-	-
12. Sulfur 660	-	-	-	-	-
13. Cheesy 2002	22.13	-	6.88	-	-
14. Unpleasant 2582	11.35	7.59	2.79	33	75
15. Fatty acid 1980	7.55	1.83	1.17	76	84
16. Fatty acid 2160	9.42	2.81	3.05	70	68
Average percent removal of each component				71	76

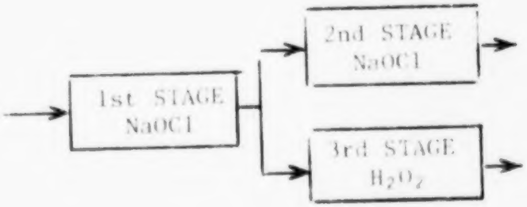

Table A-4

RESULTS OF SCRUBBING TEST 31-4
LABORATORY SCRUBBER, TIME: 9 HOURS

	Inlet	Outlet from #2 (NaOCl)	Outlet from #3 (H_2O_2)	1 → 2 % Removal	1 → 3 % Removal
Odor ED_{50}	590	45	175	92	70
GLC peaks, ug/liter air					
1. Dimethyl sulfide	69.13	4.73	7.02	93	90
2. Pungent U.P. 90	25.28	1.32	3.55	95	86
3. Dimethyl disulfide	5.52	0.33	0.05	94	99.1
4. Butyric acid	4.63	1.35	0.55	71	88
5. Propylene sulfide (cabbage 880)	1.88	2.40	0.13	-	-
6. Bitter 655	37.21	1.32	8.20	96	78
7. Burnt 1233A (pyrazine)	1.02	0.27	0.37	74	64
8. Burnt 1233B (pyrazine B)	9.91	2.19	1.10	78	89
9. Rendering 1335	193.77	25.81	6.88	87	96
10. Fatty 1545	40.93	10.22	1.62	75	96
11. Burnt 1687 (quinoline)	32.67	12.94	1.13	60	97
12. Sulfur 660	-	-	-	-	-
13. Cheesy 2002	28.32	11.53	1.82	59	94
14. Unpleasant 2582	11.93	6.72	0.83	44	93
15. Fatty acid 1980	-	-	-	-	-
16. Fatty acid 2160	-	-	-	-	-
Average percent removal of each component				77	89

Table A-5

RESIDUAL ODORS FROM SPENT SCRUBBING SOLUTIONS - TEST 31-5
LABORATORY SCRUBBER

	Inlet	Outlet from #2 (NaOCl)	Outlet from #3 (H_2O_2)
Odor ED_{50}	160	25	220
GLC peaks, ug/liter air			
1. Dimethyl sulfide	1.34	8.20	0.44
2. Pungent U.P. 90	6.11	3.57	0.90
3. Dimethyl disulfide	<0.01	<0.01	<0.01
4. Butyric acid	1.62	2.17	0.07
5. Propylene sulfide (cabbage 880)	0.58	0.33	0.09
6. Bitter 655	<0.01	0.70	3.90
7. Burnt 1233A (pyrazine)	0.34	0.44	0.15
8. Burnt 1233B (pyrazine B)	0.42	1.85	0.23
9. Rendering 1335	19.85	26.85	1.17
10. Fatty 1545	2.13	8.95	0.43
11. Burnt 1687 (quinoline)	3.15	8.43	-
12. Sulfur 660	-	-	-
13. Cheesy 2002	2.51	5.65	0.10
14. Unpleasant 2582	0.78	3.17	-
15. Fatty acid 1980	-	-	-
16. Fatty acid 2160	-	-	-

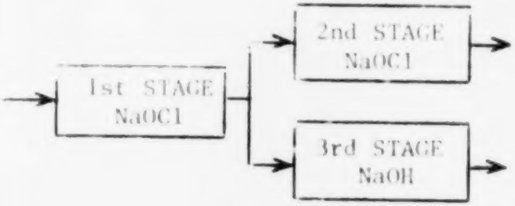

Table A-6

RESULTS OF SCRUBBING TEST 32-2
LABORATORY SCRUBBER, TIME: 1/2 HOUR

	Inlet	Outlet from #2 (NaOCl)	Outlet from #3 (NaOH)	1 → 2 % Removal	1 → 3 % Removal
Odor ED_{50}	21,500	15	35	99.9	99.8
GLC peaks, μg/liter air					
1. Dimethyl sulfide	11.82	0.95	5.09	92	57
2. Pungent U.P. 90	8.80	0.44	4.40	95	50
3. Dimethyl disulfide	1.46	0.11	0.26	92	82
4. Butyric acid	0.33	0.20	0.10	39	70
5. Propylene sulfide (cabbage 880)	0.22	0.13	0.04	41	82
6. Bitter 655	7.82	0.30	3.38	96	57
7. Burnt 1233A (pyrazine)	1.74	0.06	1.15	97	34
8. Burnt 1233B (pyrazine B)	1.75	1.14	-	-	-
9. Rendering 1335	19.25	12.72	2.07	34	89
10. Fatty 1545	3.74	1.43	0.41	62	89
11. Burnt 1687 (quinoline)	2.96	0.94	0.06	68	98
12. Sulfur 660	<0.01	0.51	3.37	-	-
13. Cheesy 2002	4.64	1.80	0.34	61	93
14. Unpleasant 2582	0.64	0.20	<0.01	69	98
15. Fatty acid 1980	1.03	0.42	<0.01	59	99
16. Fatty acid 2160	2.50	1.04	0.25	58	90
Average percent removal of each component				69	78

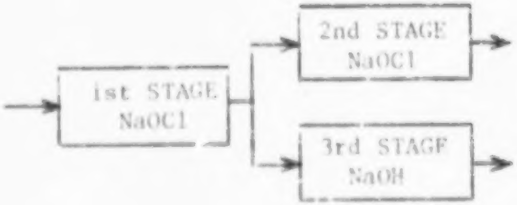

Table A-7

RESULTS OF SCRUBBING TEST 32-3
LABORATORY SCRUBBER, TIME: 2-1/2 HOURS

	Inlet	Outlet from #2 (NaOCl)	Outlet from #3 (NaOH)	1 → 2 % Removal	1 → 3 % Removal
Odor ED_{50}	2,700	35	600	98.7	78
GLC peaks, µg/liter air					
1. Dimethyl sulfide	6.73	0.87	2.17	87	68
2. Pungent U.P. 90	3.85	0.50	2.84	87	26
3. Dimethyl disulfide	5.29	0.03	0.23	99.4	96
4. Butyric acid	0.68	0.30	0.12	56	82
5. Propylene sulfide (cabbage 880)	0.75	0.05	0.04	93	95
6. Bitter 655	13.48	0.47	8.21	97	39
7. Burnt 1233A (pyrazine)	0.93	0.07	0.69	92	26
8. Burnt 1233B (pyrazine B)	1.88	0.47	0.33	75	82
9. Rendering 1335	33.45	5.94	3.38	82	90
10. Fatty 1545	6.80	1.16	0.73	83	89
11. Burnt 1687 (quinoline)	2.15	0.56	0.22	74	90
12. Sulfur 660	2.40	0.99	6.11	-	-
13. Cheese 2002	3.65	0.97	0.38	73	90
14. Unpleasant 2582	2.32	0.54	0.15	78	94
15. Fatty acid 1980	2.33	0.20	0.12	91	95
16. Fatty acid 2160	2.45	0.32	0.30	87	88
Average percent removal of each component				84	77

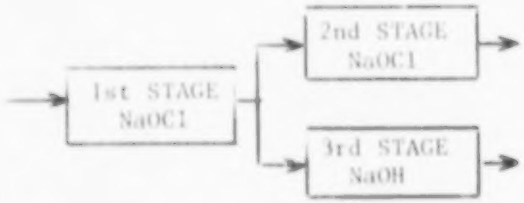

Table A-8

RESULTS OF SCRUBBING TEST 32-4
LABORATORY SCRUBBER, TIME: 8-1/2 HOURS

	Inlet	Outlet from #2 (NaOCl)	Outlet from #3 (NaOH)	1 → 2 % Removal	1 → 3 % Removal
Odor ED_{50}	5,000	450	1400	91	72
GLC peaks, μg/liter air					
1. Dimethyl sulfide	7.61	1.21	2.77	84	64
2. Pungent U.P. 90	6.55	0.16	5.15	98	21
3. Dimethyl disulfide	5.63	<0.01	0.23	99.9	96
4. Butyric acid	2.74	0.04	0.65	98.5	76
5. Propylene sulfide (cabbage 880)	4.37	0.20	0.20	95	95
6. Bitter 655	19.10	0.42	10.83	98	43
7. Burnt 1233A (pyrazine)	2.16	0.01	0.55	99.5	75
8. Burnt 1233B (pyrazine B)	4.21	0.79	0.85	81	80
9. Rendering 1335	64.72	5.63	3.98	91	94
10. Fatty 1545	36.06	1.07	1.67	97	95
11. Burnt 1687 (quinoline)	21.42	0.52	0.46	98	98
12. Sulfur 660	1.32	0.55	4.94	-	-
13. Cheesy 2002	17.71	1.11	1.05	94	94
14. Unpleasant 2582	9.16	0.40	0.41	96	96
15. Fatty acid 1980	6.89	9.19	0.36	97	95
16. Fatty acid 2160	56.09	0.88	0.59	98.4	98.9
Average percent removal of each component				95	81

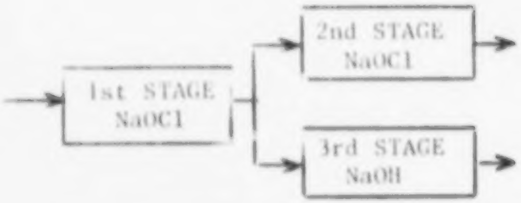

Table A-8

RESULTS OF SCRUBBING TEST 32-4
LABORATORY SCRUBBER, TIME: 8-1/2 HOURS

	Inlet	Outlet from #2 (NaOCl)	Outlet from #3 (NaOH)	1 → 2 % Removal	1 → 3 % Removal
Odor ED_{50}	5,000	450	1400	91	72
GLC peaks, μg/liter air					
1. Dimethyl sulfide	7.61	1.21	2.77	84	64
2. Pungent U.P. 90	6.55	0.16	5.15	98	21
3. Dimethyl disulfide	5.63	<0.01	0.23	99.9	96
4. Butyric acid	2.74	0.04	0.65	98.5	76
5. Propylene sulfide (cabbage 880)	4.37	0.20	0.20	95	95
6. Bitter 655	19.10	0.42	10.83	98	43
7. Burnt 1233A (pyrazine)	2.16	0.01	0.55	99.5	75
8. Burnt 1233B (pyrazine B)	4.21	0.79	0.85	81	80
9. Rendering 1335	64.72	5.63	3.98	91	94
10. Fatty 1545	36.06	1.07	1.67	97	95
11. Burnt 1687 (quinoline)	21.42	0.52	0.46	98	98
12. Sulfur 660	1.32	0.55	4.94	-	-
13. Cheesy 2002	17.71	1.11	1.05	94	94
14. Unpleasant 2582	9.16	0.40	0.41	96	96
15. Fatty acid 1980	6.89	9.19	0.36	97	95
16. Fatty acid 2160	56.09	0.88	0.59	98.4	98.9
Average percent removal of each component				95	81

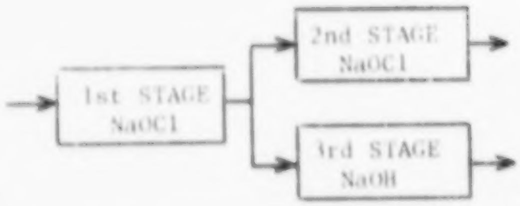

Table A-9

RESULTS OF SCRUBBING TEST 32-5
LABORATORY SCRUBBER, TIME: 17-1/2 HOURS

	Inlet	Outlet from #2 (NaOCl)	Outlet from #3 (NaOH)	1 → 2 % Removal	1 → 3 % Removal
Odor ED$_{50}$	19,000	300	370	98.4	98.1
GLC peaks, µg/liter air					
1. Dimethyl sulfide	8.75	1.10	8.45	87	3
2. Pungent U.P. 90	7.02	0.51	6.80	93	3
3. Dimethyl disulfide	3.25	0.16	2.71	95	17
4. Butyric acid	0.68	0.04	0.11	94	84
5. Propylene sulfide (cabbage 880)	0.39	0.11	0.14	72	64
6. Bitter 655	18.92	1.40	18.57	93	2
7. Burnt 1233A (pyrazine)	0.48	0.04	0.46	92	4
8. Burnt 1233B (pyrazine B)	1.52	0.03	0.09	98	94
9. Rendering 1335	26.65	4.67	3.75	82	86
10. Fatty 1545	5.83	1.12	1.22	81	79
11. Burnt 1687 (quinoline)	2.80	0.36	0.27	87	90
12. Sulfur 660	4.23	5.73	30.26	-	-
13. Cheesy 2002	3.47	0.72	0.60	79	83
14. Unpleasant 2582	0.91	0.22	0.14	76	85
15. Fatty acid 1980	1.08	0.33	0.20	70	81
16. Fatty acid 2160	9.13	0.42	1.40	95	85
Average percent removal of each component				86	57

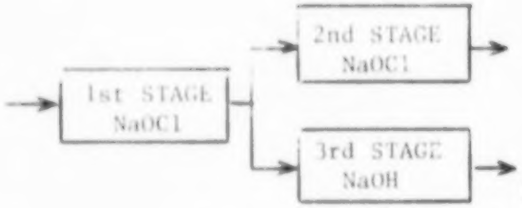

Table A-10

RESULTS OF SCRUBBING TEST 32-6
LABORATORY SCRUBBER, TIME: 24 HOURS

	Inlet	Outlet from #2 (NaOCl)	Outlet from #3 (NaOH)	1 → 2 % Removal	1 → 3 % Removal
Odor ED_{50}	16,000	240	360	98.5	98
GLC peaks, µg/liter air					
1. Dimethyl sulfide	3.56	0.39	2.23	89	37
2. Pungent U.P. 90	4.20	0.25	3.78	94	10
3. Dimethyl disulfide	0.33	0.03	0.20	91	39
4. Butyric acid	0.30	0.04	0.28	87	7
5. Propylene sulfide (cabbage 880)	0.64	0.08	0.05	88	92
6. Bitter 655	9.35	0.48	10.86	-	-
7. Burnt 1233A (pyrazine)	-	0.03	0.31	-	-
8. Burnt 1233B (pyrazine B)	-	-	-	-	-
9. Rendering 1335	49.95	7.34	12.45	85	75
10. Fatty 1545	3.65	0.98	0.90	73	75
11. Burnt 1687 (quinoline)	4.08	0.32	0.54	92	87
12. Sulfur 660	0.49	0.98	23.51	-	-
13. Cheesy 2002	3.34	0.62	0.72	81	78
14. Unpleasant 2582	1.17	0.25	0.26	79	78
15. Fatty acid 1980	4.13	0.49	0.48	88	88
16. Fatty acid 2160	18.44	0.33	0.46	98.2	98
Average percent removal of each component				87	64

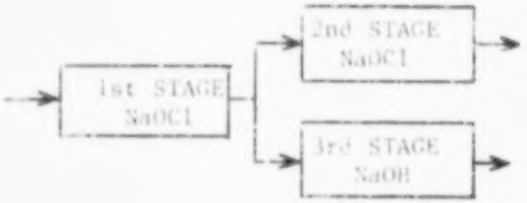

Table A-11

RESIDUAL ODORS FROM SPENT SCRUBBING SOLUTIONS - TEST 32-7 LABORATORY SCRUBBER

	Inlet	Outlet from #2 (NaOCl)	Outlet from #3 (NaOH)
Odor ED_{50}	2500	30	130
GLC peaks, μg/liter air			
1. Dimethyl sulfide		0.33	0.34
2. Pungent U.P. 90		0.05	0.73
3. Dimethyl disulfide		0.02	0.15
4. Butyric acid		0.10	0.12
5. Propylene sulfide (cabbage 850)		0.04	0.11
6. Bitter 615		0.02	1.19
7. Burnt 1233A (pyrazine)		0.04	-
8. Burnt 1233B (pyrazine B)		0.03	0.54
9. Rendering 1335		1.59	1.78
10. Fatty 1545		0.13	0.34
11. Burnt 1907 (quinoline)		0.16	0.32
12. Sulfur 660		0.90	2.18
13. Cheesy 2002		0.13	0.19
14. Unpleasant 2582		0.03	0.31
15. Fatty acid 1980		0.31	0.16
16. Fatty acid 2160		0.26	0.27

APPENDIX 2

DERIVATION OF CHEMICAL CONSUMPTION EQUATIONS

DERIVATION OF CHEMICAL CONSUMPTION EQUATIONS

1. CHLORINE REACTING WITH THE ODORANTS

During the plant life test (Test #34) the average chlorine feed rate was 12 lb/hr. From Figure 10-4, p. 10-20, the average chlorine concentration discharged to the sewer was 0.08% during a 24-hr period after the system attained equilibrium. The average blow-down rate was 2 gpm. Thus, the total chlorine used for reacting with odorants was:

$$\frac{12\ \text{lb}}{\text{HR}} - 0.0008 \left|\frac{2\ \text{gal}}{\text{min}}\right|\frac{60\ \text{min}}{\text{HR}}\left|\frac{8.34\ \text{lb}}{\text{gal}}\right. = 11.2\ \frac{\text{lb}}{\text{HR}}$$

The above chlorine consumption was based on the scrubber's operation of 24 hours a day. During the day, when the plant was not processing any material the odor removal was assumed to be 100 odor units. During the average 13 hours a day the plant processed material, plus one hour for clean-up, the measured odor levels were averaged. The actual data are presented in Section 8. The average odor removal during the evening was 720 odor units. The average odor removal over the 24-hr period would be:

$$\text{Average odor removal} = \frac{[14\ \text{hr}(720\ \text{o.u.})] + [10\ \text{hr}(100\ \text{o.u.})]}{24\ \text{hr}}$$

$$= 462\ \text{odor units}$$

Thus, assuming the chlorine reaction is a function of the Odor Quantity (odor units removed x ft^3) the following general relationship would be valid.

$$\text{Chlorine demand} = \begin{bmatrix}\text{odor units}\\ \text{removed}\end{bmatrix}(\text{CFM})\left[\frac{60\ \text{min}}{\text{hr}}\right](\text{Hours})(\text{Constant})$$

Now, if hours = 1 and combining the $\left[\frac{60\ \text{min}}{\text{hr}}\right]$ with (Constant)

$$\text{Chlorine demand} = \begin{bmatrix}\text{odor units}\\ \text{removed}\end{bmatrix}(\text{CFM})(\text{Constant}')$$

Substituting the known chlorine demand, odor units removed, and CFM, the constant can be evaluated

$$\text{Constant}' = \frac{(11.2)}{(462)(67{,}000)} = \frac{0.36}{10^6}$$

Similar calculations were made for several of the other tests. All the computed constants came out between 0.31 and 0.36, with the average value of 0.32.

Thus, the annual chlorine consumed for odor removal becomes:

$$\begin{aligned}\text{Chlorine consumed for odor removal/yr} &= \frac{0.32}{10^6}\,(\text{Odor Quantity removed})\\ &= \frac{0.32}{10^6}\,(\text{CFM})(\text{YO} - \text{YE})(\text{HRS})\end{aligned}$$

where

CFM is the volumetric gas throughput, ft^3/min

YO is the inlet odor level, odor units

YE is the scrubber outlet odor level, odor units

HRS is the total number of hours the system is operated a year

2. SCRUBBING CAPACITIES

2.1 One-Stage Scrubber

During Tests 19 and 20, the laboratory scrubber was used to investigate the performance of two stages of sodium hypochlorite followed by one stage of caustic. After Test 20, the first stage hypochlorite solution was transferred to the last stage, and a fresh batch of caustic was prepared for Tank #1. On the next test, no bag samples were collected; however, the gas chromatograms indicated very poor removals across the final stage, with several compounds showing an actual increase in concentration across the third stage. The next test, Test 22, found over half of the compounds increasing across the final stage and gave a totally unacceptable outlet odor level of 38,000 odor units. The data from Tests 19-22 are presented in Tables A2-1 through A2-4.

The solution was exposed to the incinerator inlet air for a period of 2-1/2 hours while it was in the first stage. The additional amount of odorants absorbed into this solution in the third stage was very small in comparison. Thus, the odor removal across the first stage averaged 30,000 odor units.

30,000 o.u.	2.5 Hr	60 min	17 ft^3
		HR	Min

Odor Quantity = 76,500,000 odor units - ft^3

This is the amount absorbed by the 25 gallons of first stage solution; thus,

$$\text{Scrubbing Capacity} = \frac{76{,}500{,}000\ \text{o.u.-ft}^3}{25\ \text{gal}}$$

$$= 3 \times 10^6$$

This value was checked using Test 30 data, where an average 9000 odor units were removed effectively for a 5-hr period from a 28-cfm gas stream. Test 30 also yielded a scrubbing capacity of 3×10^6.

Table A2-1

RESULTS OF SCRUBBING TEST 19
LABORATORY SCRUBBER

	(a) Inlet	(b) After 1st stage	(c) After 2nd stage	(d) Outlet	% removal
Odor ED$_{50}$	7400			400	95
GLC peaks, ng/liter air					
1. Dimethyl sulfide	Samplers overloaded		4.03	2.56	-
2. Pungent U.P. 90			3.07	2.28	-
3. Dimethyl disulfide			0.38	0.47	-
4. Butyric acid	1.59	0.14	0.08	0.05	97
5. Propylene sulfide (cabbage 880)	2.57	0.56	0.85	0.57	78
6. Bitter 655	-	-	-	-	-
7. Burnt 1233A (pyrazine)	1.80	0.26	0.09	0.05	97
8. Burnt 1233B (pyrazine B)	1.61	0.37	0.13	0.07	96
9. Rendering 1335	66.72	7.25	1.37	0.49	99.3
10. Fatty 1545	15.79	1.56	0.72	0.12	99.2
11. Burnt 1687 (quinoline)	7.91	0.48	0.28	0.12	98.5
12. Sulfur 660	-	-	-	-	-
13. Cheesy 2002	14.62	0.83	0.47	0.08	99.5
14. Unpleasant 2582	3.45	0.39	0.15	0.06	98.3
15. Fatty acid 1980	3.41	-	0.10	0.13	96
16. Fatty acid 2160	3.40	-	0.28	0.09	97
Average percent removal of each component					96

Table A2-2

RESULTS OF SCRUBBING TEST 20
LABORATORY SCRUBBER

	(a) Inlet	(b) After 1st stage	(c) After 2nd stage	(d) Outlet	% removal
Odor ED_{50}	76,000			170	99.8
GLC peaks, μg/liter air					
1. Dimethyl sulfide	Sampler overloaded	Sampler overloaded	1.60	1.65	
2. Pungent U.P. 90			-	-	
3. Dimethyl disulfide			0.24	0.21	
4. Butyric acid			0.07	0.15	
5. Propylene sulfide (cabbage 880)			0.22	0.20	
6. Bitter 655			-	-	
7. Burnt 1233A (pyrazine)			0.05	0.02	
8. Burnt 1233B (pyrazine B)			0.09	0.26	
9. Rendering 1335			1.40	0.77	
10. Fatty 1545			0.27	0.15	
11. Burnt 1687 (quinoline)			0.09	0.09	
12. Sulfur 660			-	-	
13. Cheesy 2002			0.05	0.11	
14. Unpleasant 2582			0.06	0.32	
15. Fatty acid 1980		0.82	0.08	0.04	
16. Fatty acid 2160		1.59	0.37	0.22	

Average percent removal of each component

Table A2-3

RESULTS OF SCRUBBING TEST 21
LABORATORY SCRUBBER

	(a) Inlet	(b) After 1st stage	(c) After 2nd stage	(d) Outlet	% removal
Odor ED$_{50}$					
GLC peaks, ng/liter air					
1. Dimethyl sulfide	-	3.12	2.75	2.69	-
2. Pungent U.P. 90	4.46	1.84	1.26	0.78	83
3. Dimethyl disulfide	0.71	0.34	0.33	0.11	85
4. Butyric acid	0.38	0.20	0.12	0.13	66
5. Propylene sulfide (cabbage 880)	0.12	0.17	0.04	0.03	75
6. Bitter 655	-	-	-	-	-
7. Burnt 1233A (pyrazine)	0.88	0.80	0.39	0.23	74
8. Burnt 1233B (pyrazine B)	1.14	0.50	0.21	0.14	88
9. Rendering 1335	12.82	3.95	0.64	0.41	97
10. Fatty 1545	2.35	1.65	0.26	0.15	94
11. Burnt 1687 (quinoline)	1.48	0.67	0.12	0.13	91
12. Sulfur 660	-	-	-	-	-
13. Cheese 2002	4.67	1.34	0.06	0.13	97
14. Unpleasant 2582	0.51	0.38	0.08	0.18	65
15. Fatty acid 1980	1.74	0.29	0.41	0.06	97
16. Fatty acid 2160	2.97	0.84	0.22	0.12	96
Average percent removal of each component					85

Table A2-4

RESULTS OF SCRUBBING TEST 22
LABORATORY SCRUBBER

	(a) Inlet	(b) After 1st stage	(c) After 2nd stage	(d) Outlet	% removal
Odor ED$_{50}$	46,000			38,000	17
GLC peaks, ng/liter air					
1. Dimethyl sulfide	13.25	5.96	2.92	4.63	65
2. Pungent U.P. 90	4.64	2.57	1.30	0.60	87
3. Dimethyl disulfide	1.67	0.70	0.24	0.14	92
4. Butyric acid	2.22	0.22	0.08	0.21	91
5. Propylene sulfide (cabbage 880)	1.52	0.44	0.32	0.09	94
6. Bitter 655	-	-	-	-	-
7. Burnt 1233A (pyrazine)	0.75	0.66	0.19	0.26	65
8. Burnt 1233B (pyrazine B)	4.53	1.59	0.96	0.52	89
9. Rendering 1335	53.14	10.37	2.11	7.15	87
10. Fatty 1545	16.50	1.86	0.37	1.22	93
11. Burnt 1687 (quinoline)	6.02	0.45	0.08	1.18	80
12. Sulfur 660	-	-	-	-	-
13. Cheesy 2002	9.56	1.51	0.23	1.66	83
14. Unpleasant 2582	9.36	0.51	0.08	0.30	97
15. Fatty acid 1980	1.92	0.31	0.07	0.25	87
16. Fatty acid 2160	6.05	1.35	0.22	0.25	96
Average percent removal of each component					86

2.2 Two-Stage Scrubber

In Test 32, a two-stage sodium hypochlorite system was operated for 24 hours while effectively removing the odorous compounds. During this period of time, the odor level reduction averaged 12,000 odor units across the two-stage laboratory scrubber. Each scrubbing solution contained 20 gallons.

$$\text{Odor Quantity} = \frac{12{,}000\ \text{o.u.}/17\ \text{ft}^3/24\ \text{HR}/60\ \text{min}}{/\ \text{min}\ /\qquad /\ \text{HR}}$$

$$= 293{,}000{,}000\ \text{o.u.-ft}^3$$

$$\text{Scrubbing Capacity} = \frac{\text{Odor Quantity}}{40\ \text{gallons}}$$

$$= 7\text{x}10^6$$

2.3 Three-Stage Scrubber

During the Plant Liquor Life Test, utilizing the continuous blow-down system, the average odor reduction was 540 odor units, as developed in Appendix 1.

$$\text{Odor Quantity} = 540\ \text{odor units}\left(67{,}000\ \frac{\text{ft}^3}{\text{min}}\right)$$

$$= 36{,}000{,}000\ \text{o.u.-ft}^3/\text{min}$$

$$\text{Scrubbing Capacity} = \frac{\text{Odor Quantity}}{2\ \text{gpm blow-down}}$$

$$= 18\text{x}10^6$$

Because only one or two samples were measured each day, the average odor reduction is subject to considerable error. The laboratory liquor life test using the continuous blow-down and make-up system was also checked.

$$\text{Odor Quantity} = \frac{15{,}000\ \text{o.u.}/17\ \text{ft}^3/60\ \text{min}}{/\ \text{min}\ /\ \text{hr}}$$

$$= 15\text{x}10^6\ \text{o.u.-ft}^3/\text{hr}$$

$$\text{Scrubbing Capacity} = \frac{\text{Odor Quantity}}{1.5\ \text{gal/hr blow-down}}$$

$$= 10\text{x}10^6$$

The wide variation for scrubbing capacities is probably due to the uncertainty in the average odor reduction. In Chapter 9, additional reasons why the scrubbing capacity in the laboratory liquor life test was lower than in the plant test are provided. However, an average of the two values will be used.

Three stage scrubbing capacity = 14×10^8

3. ANNUAL CHLORINE LOSS TO SEWER

Based on Section 10.3.1.2, the chlorine loss to the sewer as a function of the total chlorine consumed is

	Chlorine loss
1 stage	54%
2 stages	25%
3 stages	8%

The amount of chlorine reacted with the odorants (Cl_2-RX) is determined by the odor level and gas throughput. The chlorine loss to the sewer (Cl_2-LOSS) can be written in terms of Cl_2-RX. Based on the above table, the following was developed:

	Ratio $\frac{Cl_2\text{-LOSS}}{Cl_2\text{-RX}}$
1 stage	$\frac{54\%}{100 - 54\%} = 1.17$
2 stages	$\frac{25\%}{100 - 25\%} = 0.33$
3 stages	$\frac{8\%}{100 - 8\%} = 0.085$

The following equation can be written

$$Cl_2\text{-LOSS} = f(x)(Cl_2\text{-RX})$$

where f(x) should equal Cl_2-LOSS/Cl_2-RX as shown in the above table. Plotting Cl_2-LOSS/Cl_2-RX versus the number of stages on semi-log paper, a straight line is developed having a slope of -1.278 and an intercept of ln 4.2. Thus, the following relationship holds

$$Cl_2\text{-LOSS} = (Cl_2\text{-RX})4.2\ \exp(-1.278NS)$$

where NS is the number of stages

4. CAUSTIC CONSUMPTION DUE TO REACTION WITH ODOROUS COMPOUNDS

In Test 32, using the laboratory scrubber, the caustic levels were monitored throughout the test using pH titrations. The pH in both the first and the second stages was held at the same level, thus both would remove the same amount of CO_2. The different caustic consumption rates between the first stage and the second stage would be due to the greater reaction of odorous compounds in the first stage where odor levels are higher. For the last six hours of Test 32, the caustic level dropped 1.4 lb in the first stage and 1.2 lb in the second stage. Because the first stage was removing an average of 12,000 odor units per cfm (93%) while the second stage was removing an average of only 800 odor units per cfm (93%), the organic content in the second stage was insignificant (less than 10%) as compared to the organic content in the first stage. Thus, 0.2 lb were consumed in the first stage due to the higher odor level.

$$0.2 \text{ lb NaOH} = \text{Constant}(\text{YO} - \text{YE})(\text{CFM})(\text{HRS})$$

or

$$\text{Constant} = \frac{0.2 \text{ pounds}}{(12{,}000 \text{ odor units})(28 \text{ cfm})(6 \text{ hours})}$$

$$= \frac{0.1}{10^6}$$

Thus, the final equation becomes:

$$\text{Annual caustic consumption due to reaction with odorants} = \frac{0.1}{10^6}(\text{YO} - \text{YE})(\text{CFM})(\text{HRS})$$

This equation was checked with the total caustic consumption for the plant life test and was found to give values within 15% of the measured rates.

APPENDIX 3

CALIBRATION OF THE HORIZONTAL SPRAY SCRUBBER MODEL

CALIBRATION OF THE HORIZONTAL SPRAY SCRUBBER MODEL

1. INTRODUCTION

As mentioned in Chapter 11, the model for spray scrubbers utilizes the penetration theory to calculate the mass transfer of odorous compounds from the gas phase to the liquid droplets. Data collected during the first part of this program was used to check the model.

2. NOMENCLATURE FOR SPRAY SCRUBBER

a	Area available for mass transfer, surface area of drops, ft^2/ft^3
θ_c	Contact time of drops in scrubber, hr
Diff	Diffusivity of odorant vapor in air, ft^2/hr
L_{noz}	Flow of liquid per nozzle, gal/min
Z	Height of scrubber, ft
X_L	Length of a scrubber stage, ft
X_x	Log of odor reduction ratio
k_g	Mass transfer coefficient, $lb\text{-}mol/hr\text{-}ft^2\text{-}atm$
G_M	Molar gas flow rate, $lb\text{-}mol/hr\text{-}ft^2$
n_1	Number of collisions per drop per sec
W	Width of scrubber, ft
N_{oza}	Number of nozzles per sq ft of scrubber cross section
T	Temperature of gas stream, °R
CFM	Total air flow, cu ft/min
P_T	Total pressure, atm

3. DESIGN EQUATION FROM PENETRATION THEORY

The success of the horizontal spray scrubber depends on the use of low air velocities such that the droplets remain in the scrubber for a second. Previously designed spray scrubbers either have insufficient droplet area/unit volume or insufficient contact time. Although the nozzles point upstream, the stopping distance of droplets is such that they soon acquire the air velocity and drift down the scrubber to the exit. Therefore, the droplet contact time was set equal to the air contact time in the scrubber.

According to the methods of calculation used, each droplet acts independently of the others. Actually the droplets can collide and coalesce. This effect was computed to see if it is significant, but it was not compensated for.

The equation for mass transfer is the same as that for a packed scrubbing tower (Eq 4, p. 10-6). Only the method of calculating the mass transfer coefficient is different.

The mass transfer coefficient is predicted from penetration theory based on the transient diffusion of odorant through the gas layer adjacent to each drop. The result is:

$$k_g = \frac{2}{RT}\sqrt{\frac{Diff}{\pi\theta_c}}\quad\frac{\text{lb-mol}}{\text{hr-ft}^2\text{-atm}}$$

The contact time, θ_c, of droplets in the air depends on the length of scrubber X_L and the gas (and droplet) velocity.

The resulting design equation is:

$$\frac{X_L k_g a P_T}{G_m} = \frac{2\ T\ a}{460}\sqrt{\frac{Diff X_L W\ Z}{60\pi\ cfm}}$$

We now design the scrubber by fixing the length $X_L = 8$ ft, as is done by Air Conditioning Corporation, and vary the area WZ. In doing so, we allow the number of nozzles per unit of cross-sectional area N_{oza} to remain constant; the total number increases with area. The liquid flow per nozzle L_{noz} is also fixed; so changing the height changes the liquid flow and increases the droplet area. It also decreases the air velocity and increases the contact time. As a result, the capacity depends on area$^{3/2}$. These substitutions are included in the design computer program.

The flow rate per nozzle, L_{noz}, is another variable that affects the design, and hence the scrubbing cost. The program provides for reading in four values of L_{noz}; it computes the scrubber design and cost for each, and chooses the most economic one. Other variables, such as spray nozzle pressure, affect droplet size and power. These can be explored by trial calculations with the program.

Costs of each component of equipment and operating costs are similar to those used for the packed tower scrubber. These equations were given in Report No. EPA-R2-72-088 and are included in the computer program.

The drop collision rate is estimated by applying equations from the kinetic gas theory. In most cases, the decrease in number of drops due to collision is small, but it could be large if a high droplet concentration is produced.

4. COMPARISON OF MODEL WITH EXPERIMENT

The user of the model specifies the desired performance, the number of stages, and the length of each contact chamber. The model then computes the cross-sectional area (and associated number of nozzles) required to achieve the specified removal. The scrubber at the Des Moines rendering plant had the following characteristics:

52 ft^2 cross-sectional area
6 nozzles/ft^2
1.2 gpm/nozzle (measured)
60,000 acfm (measured)
3 stages, each with 8-ft long contact chamber

Using the above design features, one need only specify the desired odor removal and compare the cross-sectional area obtained. At the time of this verification, only ten scrubbing tests had been performed using the plant scrubber. The removals from the best four tests were averaged to represent the expected performance utilizing the optimum scrubbing solutions.

Test No.	Inlet ED$_{50}$	Outlet ED$_{50}$	Odor Panel % Removal
8	320	20	94
12	360	35	90
15	660	25	96
16	300	70	77
	Average % Removal		89%

Thus, by specifying a removal of approximately 90%, one would expect the model to predict a required cross-sectional area near 52 ft^2 if the model is accurate. The results of the computer run, shown in Table A3-1, predicted a required cross-sectional area of 58.8 ft^2 for 90% removal. Thus, the model predicted within 13% of the actual dimensions of the Des Moines scrubber.

APPENDIX 4

DEVELOPMENT OF THE PACKED-TOWER MASS TRANSFER EQUATION

DEVELOPMENT OF THE PACKED-TOWER MASS TRANSFER EQUATION

In Section 10.2, the mass transfer equation for packed towers was developed in detail, with the resulting final equation:

$$K_Ga = \text{Constant}\left(\frac{L}{1,000}\right)^{0.27} \text{PKGA}$$

where

K_Ga is mass transfer rate, lb-moles/hr-ft^3-atm

L is liquid mass flux, lb/hr/ft^2

PKGA is ratio of the mass transfer rate (K_Ga) of the packing used, compared to the mass transfer rate of 1-1/2-in. Intalox saddles

In order to determine the value of the "Constant", the experimental results from the three-stage laboratory scrubber were utilized. The laboratory scrubber utilizes 1/2-in. Intalox saddles; thus:

$$\text{PKGA} = \frac{K_Ga \text{ 1/2-in. Intalox saddles}}{K_Ga \text{ 1-1/2-in. Intalox saddles}}$$

at the same conditions. Norton (1969) presents mass transfer data for both the 1/2-in. and the 1-1/2-in. Intalox saddles. At a liquid mass flux rate of 2,000 lb/hr/ft^2, which is the same rate used in the laboratory scrubber, the ratio of K_Ga is given at 2.06. This ratio only changes 10% when increasing the liquid rate to 6,000 lb/hr/ft^2. Thus, a value of PKGA of 2.06 was utilized to determine the constant.

At the time of the development of the "Constant", only a limited number of tests had been performed using the laboratory scrubber. As various scrubbing liquor combinations were being compared for their effectiveness, only the most efficient removals were averaged; these values are tabulated below.

Test No.	Odor Panel % Removal
7	99.7
10	98.6
11	99.1
15	99.8
23	99.8
Average	99.4

For the computer model, the inlet and outlet odor levels are specified and the optimum scrubber dimensions are computed. Using an inlet odor level of 10,000 odor units and an outlet odor level of 58 odor units (99.4% removal), the "Constant" term was varied until the proper scrubber dimensions were predicted. Using the following equation, the computer model predicted that 3 stages of 2 ft of packing would be required:

$$K_Ga = 4.5 \left(\frac{L}{1,000}\right)^{0.27} \text{PKGA}$$

The results of the computer model are presented in Table A4-1.

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Table A4-1
LABORATORY SCRUBBER DESIGN CALCULATIONS

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[illegible]
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[illegible]
[illegible]
  .[illegible]   [illegible]                              [illegible]

[illegible]

FLOW RATE   [illegible]
   CFM      [illegible]
   17.      [illegible]

[illegible]

[illegible]

[illegible]

          CHEMICAL CONSUMPTION
          CAUSTIC       CHLORINE
          LB/YEAR       LB/YEAR
             [illegible]            [illegible]

          CAPITAL COSTS FOR SCRUBBER SYSTEM
TOWER     INTERNALS     PACKING     FAN     [illegible]     [illegible]     [illegible]     TOTAL
[illegible]

          ANNUAL COST FOR [illegible]
[illegible]

E121.  COST [illegible]
```

Table A4-1 Continued

```
                  CHAMBER                       TOTAL
NOZZLES/UNIT FT   LENGTH    UNITS/SERIES        LENGTH   NOZZLE PSI
     4.0           8.0          3.0             52.0        16.8
GPM/NOZZLE
    1.200     10.000    15.000    20.000    25.000

                UNIT COSTS FOR SCRUBBER SYSTEM
POWER      MAINTENANCE      NOZZLES       AMORTIZATION
$/KWH      $/SQFT(CFM)       $ EA            FACTOR
 .025         8.000          5.000           .100

FLOW RATE   CONCENTRATION    HENRY   SCHMIDT NO   TEMPERATURE
  CFM       INLET  OUTLET                          DEGREES F
 66000.     1000.   50.       0.         0.             70.

            INTERMEDIATE VALUES DURING OPTIMIZATION
 ANNUAL COST  CAPITAL  TIME-SEC  HEIGHT  GPM/NOZ  FT2/FT3  NO  F1
   29715.     108304.     1.4      8.4      1.2      4.1  785122  774675
    29715.
   32074.      88192.      .4      2.1     10.0      7.3  666425  646049
   33390.      87114.      .3      2.1     15.0      8.1  660015  617289
   34556.      86791.      .3      1.8     20.0      8.8  656930  595490
   35500.      86784.      .3      1.6     25.0      9.4  647708  577667
   29715.     108304.     1.4      8.4      1.2      4.1  785122  774675
    29715.

            OPERATING CONDITIONS OF TOWER-CALCULATED
       THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
SCRUBBER WIDTH      SCRUBBER HEIGHT      TOTAL FLOW RATES
    FEET                 FEET          GAS(CFM)     LIQUID(GPM)
     7.0                  8.4           66000.0         424.7

NOZZLES/BANK      BANKS/UNIT      DROP UM      UNITS/SERIES
    354.              1.            381.             3.

        PRESSURE DROP     FAN HORSEPOWER     PUMP HORSEPOWER
            4.500            77.073              11.940

           CHEMICAL CONSUMPTION
           CAUSTIC       CHLORINE
           LB/YEAR       LB/YEAR
           66025.         33241.

           CAPITAL COSTS FOR SCRUBBER SYSTEM
  SHELL    NOZZLES     FAN     PUMP     MOTORS     TANKS     EXTERNALS     TOTAL
 47501.    5308.      891.    1880.     4092.     7454.      41378.      108304.

                ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION    POWER   MAINTENANCE   CHEMICALS    TOTAL    $/1000CFM-HR
 10830.        10527.    3394.          4963.     29715.        .000
```

APPENDIX 5

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS

Table A5-1

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS

Case 1

```
         NUMBER OF STAGES IN SCRUBBER IS 1.

         TYPE OF PACKING AND ITS PROPERTIES
         1 1/2 INTALOX SADDLES
         POROSITY       AREA      EQUIVALENT      CONSTANTS FOR DELTAP
                     SQFT/CUFT   DIAMETER(FT)       ALPHA     BETA
            .810        52.0          .16            .130     .150

         OPERATING CONDITIONS FOR TOWER

FLOW RATE   CONCENTRATION    HENRY   SCHMIDT NO   TEMPERATURE
   CFM      INLET  OUTLET                          DEGREES F
  5000.     8000.    40.      0.        2.053          70.

              UNIT COSTS FOR SCRUBBER SYSTEM
      POWER   MAINTENANCE      PACKING     AMORTIZATION
      $/KWH   $/SQRT(CFM)      $/CU-FT        FACTOR
      .025       8.000          8.200        .130

          INTERMEDIATE VALUES DURING OPTIMIZATION
ANNUAL COST      LOADING RATES(LB/HR-SQFT)
                 LIQUID       GAS        CAPITAL-$      HTUG(FT)      K(G)A      PACKING DEPTH          DIAMETER
   33778.        1000.        1812.        33216.        13.882       4.5000         73.6                   3.98
   31068.        2500.        1414.        28347.         8.458       5.7631         44.8                   4.50
   30292.        4000.        1189.        26679.         6.284       6.5429         33.2                   4.91
   29980.        5500.        1031.        25969.         4.986       7.1303         26.4                   5.27
   29860.        7000.         909.        25729.         4.121       7.6101         21.8                   5.61
   29844.        8500.         811.        25778.         3.466       8.0107         18.5                   5.95

          OPERATING CONDITIONS OF TOWER-CALCULATED
       THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
    TOWER DIAMETER     PACKING DEPTH     LOADING RATES       TOTAL FLOW RATES
       FEET                FEET          LBS/HR-SQFT       GAS(CFM)    LIQUID(GPM)
       5.95                18.5          810.7   8500.      5000.        470.

       PRESSURE DROP      FAN HORSEPOWER      PUMP HORSEPOWER
            3.7               5.2                 6.8

            CHEMICAL CONSUMPTION
            CAUSTIC      CHLORINE
            LB/YEAR      LB/YEAR
            151433.       110553.

            CAPITAL COSTS FOR SCRUBBER SYSTEM
   TOWER    INTERNALS      PACKING     FAN      PUMP      MOTORS      TANKS       TOTAL
  16350.      610.           4204.     358.      681.       868.      2706.       25778.

               ANNUAL COST FOR SCRUBBER SYSTEM
         AMORTIZATION   POWER   MAINTENANCE   CHEMICAL      TOTAL     $/1000 CFM-HR
             3351.        895.     566.        25033.        29844.       1.492
6121.   6003  END OF PROGRAM
-
```

Table A5-2

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS

Case 2

```
                    NUMBER OF STAGES IN SCRUBBER IS 2.

                    TYPE OF PACKING AND ITS PROPERTIES
                    1 1/2 INTALOX SADDLES
                    POROSITY      AREA       EQUIVALENT      CONSTANTS FOR DELTAP
                                SQFT/CUFT    DIAMETER(FT)       ALPHA     BETA
                      .810        52.0          .16              .130     .150

                     OPERATING CONDITIONS FOR TOWER
  FLOW RATE   CONCENTRATION    HENRY    SCHMIDT NO   TEMPERATURE
    CFM       INLET  OUTLET                           DEGREES F
   5000.      8000.    40.     0.         2.053            70.

          POWER    UNIT COSTS FOR SCRUBBER SYSTEM
          $/KWH    MAINTENANCE      PACKING      AMORTIZATION
           .025    $/SQRT(CFM)      $/CU-FT        FACTOR
                     8.000          8.200          .130

             INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST     LOADING RATES(LB/HR-SQFT)
                     LIQUID      GAS      CAPITAL-$     HTUG(FT)    K(G)A     PACKING DEPTH      DIAMETER
    25424.           1000.      1812.      38226.       13.882     4.5000        36.8              3.98
    22805.           2500.      1414.      33898.        8.458     5.7631        22.4              4.50
    22149.           4000.      1189.      32936.        6.264     6.5429        16.6              4.91
    21970.           5500.      1031.      32995.        4.986     7.1303        13.2              5.27
    21996.           7000.       909.      33572.        4.121     7.6101        10.9              5.61

               OPERATING CONDITIONS OF TOWER-CALCULATED
            THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
    TOWER DIAMETER      PACKING DEPTH      LOADING RATES         TOTAL FLOW RATES
      FEET                 FEET           LBS/HR-SQFT        GAS(CFM)    LIQUID(GPM)
      5.61                 10.9           909.5    7000.       5000.       345.

       PRESSURE DROP       FAN HORSEPOWER        PUMP HORSEPOWER
            4.7                 6.7                   3.6

            CHEMICAL CONSUMPTION
            CAUSTIC       CHLORINE
            LB/YEAR       LB/YEAR
             98285.        67550.

                CAPITAL COSTS FOR SCRUBBER SYSTEM
    TOWER      INTERNALS     PACKING     FAN      PUMP      MOTORS     TANKS      TOTAL
   21046.       1050.         4429.      358.     1099.     1093.      4496.      33572.

                 ANNUAL COST FOR SCRUBBER SYSTEM
           AMORTIZATION   POWER   MAINTENANCE   CHEMICAL      TOTAL     $/1000 CFM-HR
              4364.       1047.      800.        15785.       21996.        1.100
6121.   6003  END OF PROGRAM
-
```

Table A5-3

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS

Case 3

```
                 NUMBER OF STAGES IN SCRUBBER IS 3.

                 TYPE OF PACKING AND ITS PROPERTIES
                 1 1/2 INTALOX SADDLES
                 POROSITY        AREA      EQUIVALENT      CONSTANTS FOR DELTAP
                               SQFT/CUFT  DIAMETER(FT)       ALPHA     BETA
                   .810          52.0          .16            .130      .150


                 OPERATING CONDITIONS FOR TOWER

 FLOW RATE   CONCENTRATION   HENRY   SCHMIDT NO   TEMPERATURE
   CFM       INLET  OUTLET                         DEGREES F
   5000.     8000.    40.    0.        2.053          70.

                 UNIT COSTS FOR SCRUBBER SYSTEM
        POWER     MAINTENANCE      PACKING      AMORTIZATION
        $/KWH      $/SQRT(CFM)      $/CU-FT         FACTOR
         .025        8.000          8.200         .130

        INTERMEDIATE VALUES DURING OPTIMIZATION
 ANNUAL COST     LOADING RATES(LB/HR-SQFT)
                 LIQUID      GAS       CAPITAL-$      HTUG(FT)      KGA/A     PACKING DEPTH      DIAMETER
    23553.       1000.      1913.       42013.        13.009       4.5000       24.7               3.08
    21042.       2500.      1314.       39949.         8.659       5.7671       14.9               4.57
    20513.       4000.      1190.       39952.         6.266       6.5400       11.1               4.01
    20473.       5500.      1031.       39927.         4.906       7.1303        9.9               5.27
    20551.       7000.       900.       41360.         4.721       7.6101        7.7               5.81
    20542.       6250.       950.       40665.         4.892       7.7907        7.9               5.47
    20466.       5500.      1023.       39902.         4.910       7.1363        8.7               5.29
    20448.       4750.      1006.       39453.         5.517       6.8536        9.7               5.11


             OPERATING CONDITIONS OF TOWER-CALCULATED
         THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
      TOWER DIAMETER     PACKING DEPTH     LOADING RATES     TOTAL FLOW RATES
        FEET                FEET          LBS/HR-SQFT    GAS(CFM)   LIQUID(GPM)
        5.11                9.7          1006.5   4750.     5000.      104

        PRESSURE DROP     FAN HORSEPOWER     PUMP HORSEPOWER
              7.4              10.6               1.9

             CHEMICAL CONSUMPTION
             CAUSTIC       CHLORINE
             LB/YEAR       LB/YEAR
              82415.        55560.

             CAPITAL COSTS FOR SCRUBBER SYSTEM
   TOWER     INTERNALS      PACKING      FAN      PUMP      MOTORS      TANKS      TOTAL
  25756.      1235.           4915.     358.     1165.     1247.      4777.       39453.

                  ANNUAL COST FOR SCRUBBER SYSTEM
          AMORTIZATION   POWER   MAINTENANCE   CHEMICAL       TOTAL      $/1000 CFM-HR
              5129.      1222.     980.         13118.        20448.        1.022
```

Table A5-4

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS
Case 4

```
                    NUMBER OF STAGES IN SCRUBBER IS 3.

                    TYPE OF PACKING AND ITS PROPERTIES
                    1 1/2 INTALOX SADDLES
                    POROSITY         AREA      EQUIVALENT       CONSTANTS FOR DELTAP
                                   SQFT/CUFT  DIAMETER(FT)       ALPHA    BETA
                       .810         52.0          .16             .130     .150


                    OPERATING CONDITIONS FOR TOWER

 FLOW RATE    CONCENTRATION    HENRY    SCHMIDT NO    TEMPERATURE
   CFM        INLET  OUTLET                           DEGREES F
  10000.      8000.    20.      0.         2.053           70.

                    UNIT COSTS FOR SCRUBBER SYSTEM
          POWER     MAINTENANCE      PACKING      AMORTIZATION
          $/KWH      $/SQRT(CFM)      $/CU-FT         FACTOR
           .025        8.000          8.200          .130

            INTERMEDIATE VALUES DURING OPTIMIZATION
 ANNUAL COST      LOADING RATES(LB/HR-SQFT)
                    LIQUID       GAS         CAPITAL-$        HTUG(FT)       K(G)A      PACKING DEPTH        DIANETER
    46248.          1000.       1812.         75052.          13.882        4.5000        27.7                 5.63
    40675.          2500.       1414.         67733.           8.458        5.7031        16.0                 6.37
    39380.          4000.       1186.         66792.           6.264        6.5420        12.5                 6.94
    39147.          5500.       1031.         67795.           4.986        7.1303        10.0                 7.40
    39357.          7000.        900.         69810.           4.121        7.6101         8.2                 7.94
    39202.          6250.        950.         68830.           4.482        7.3807         9.0                 7.73
    39131.          5500.       1023.         67903.           4.949        7.1303         9.0                 7.48
    39168.          4750.       1006.         67218.           5.517        6.9530        11.0                 7.23


                 OPERATING CONDITIONS OF TOWER-CALCULATED
            THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
      TOWER DIAMETER       PACKING DEPTH      LOADING RATES      TOTAL FLOW RATES
          FEET                 FEET           LBS/HR-SQFT      GAS(CFM)    LIQUID(GPM)
          7.23                 11.0          1006.5     4750.     10000.        388.

          PRESSURE DROP      FAN HORSEPOWER       PUMP HORSEPOWER
               8.4               23.0                  4.1

                 CHEMICAL CONSUMPTION
                 CAUSTIC        CHLORINE
                 LB/YEAR        LB/YEAR
                 165634.         111421.

                 CAPITAL COSTS FOR SCRUBBER SYSTEM
      TOWER      INTERNALS       PACKING       FAN       PUMP      MOTORS      TANKS       TOTAL
     41378.       3041.          11128.        576.      1730.     2114.       7241.       67218.

                       ANNUAL COST FOR SCRUBBER SYSTEM
               AMORTIZATION    POWER    MAINTENANCE     CHEMICAL        TOTAL      $/1000 CFM-HR
                   8738.       2709.      1386.          26335.         39168.          .979

 6121.    6003  END OF PROGRAM
```

Table A5-5

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS
Case 5

```
                 NUMBER OF STAGES IN SCRUBBER IS 1.

                 TYPE OF PACKING AND ITS PROPERTIES
                 1 1/2 INTALOX SADDLES
                 POROSITY       AREA      EQUIVALENT     CONSTANTS FOR DELTAP
                             SQFT/CUFT  DIAMETER(FT)        ALPHA     BETA
                   .810        52.0         .16              .130     .150


                 OPERATING CONDITIONS FOR TOWER

FLOW RATE   CONCENTRATION    HENRY    SCHMIDT NO   TEMPERATURE
   CFM       INLET  OUTLET                           DEGREES F
  25000.      500.    10.     0.          2.053           70.

                 UNIT COSTS FOR SCRUBBER SYSTEM
        POWER      MAINTENANCE       PACKING      AMORTIZATION
        $/KWH      $/SQRT(CFM)       $/CU-FT         FACTOR
         .025         8.000          8.200          .130

        INTERMEDIATE VALUES DURING OPTIMIZATION
 ANNUAL COST     LOADING RATES(LB/HR-SQFT)
                 LIQUID       GAS        CAPITAL-$      HTU(FT)      K(G)A     PACKING DEPTH        DIAMETER
    35699.        1000.       1832.       86010.        13.882      4.5000        54.7              8.59
    26740.        2500.       1414.       75873.         9.458      5.7631        33.1             10.07
    24510.        4000.       1188.       74322.         6.264      6.5420        24.5             10.98
    23809.        5500.       1031.       74932.         4.986      7.1303        19.5             11.79
    23737.        7000.        909.       76392.         4.121      7.6101        16.1             12.55
    24010.        8500.        811.       78653.         3.466      8.0107        13.6             13.30
    23836.        7750.        850.       77701.         3.747      7.8221        14.7             12.95
    23724.        7000.        901.       76625.         4.085      7.6101        16.0             12.61
    23697.        6250.        959.       75710.         4.480      7.3807        17.5             12.23


             OPERATING CONDITIONS OF TOWER-CALCULATED
        THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
     TOWER DIAMETER     PACKING DEPTH     LOADING RATES     TOTAL FLOW RATES
         FEET               FEET          LBS/HR-SQFT    GAS(CFM)    LIQUID(GPM)
        12.2                17.5          959.9   6250.    25000.      1460.

        PRESSURE DROP     FAN HORSEPOWER      PUMP HORSEPOWER
              3.9              28.0                20.3

             CHEMICAL CONSUMPTION
             CAUSTIC      CHLORINE
             LB/YEAR      LB/YEAR
              61670.        34027.

             CAPITAL COSTS FOR SCRUBBER SYSTEM
   TOWER     INTERNALS       PACKING      FAN      PUMP      MOTORS      TANKS       TOTAL
  44915.      3971.           16862.     1115.    1297.      2206.      5344.        75710.

                 ANNUAL COST FOR SCRUBBER SYSTEM
          AMORTIZATION   POWER  MAINTENANCE   CHEMICAL       TOTAL     $/1000 CFM-HP
              9842.      3605.   1265.           8985.       23697.          .277
```

Table A5-6

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS
Case 6

```
          NUMBER OF STAGES IN SCRUBBER IS 2.

          TYPE OF PACKING AND ITS PROPERTIES
          1 1/2 INTALOX SADDLES
          POROSITY        AREA      EQUIVALENT      CONSTANTS FOR DELTAP
                        SQFT/CUFT   DIAMETER(FT)      ALPHA     BETA
             .810         52.0          .16            .130      .150

          OPERATING CONDITIONS FOR TOWER

FLOW RATE   CONCENTRATION   HENRY   SCHMIDT NO   TEMPERATURE
   CFM       INLET  OUTLET                        DEGREES F
 25000.       500.    10.     0.        2.053          70.

          UNIT COSTS FOR SCRUBBER SYSTEM
     POWER     MAINTENANCE      PACKING      AMORTIZATION
     $/KWH     $/SQRT(CFM)      $/CU-FT         FACTOR
      .025        8.000          8.200          .130

     INTERMEDIATE VALUES DURING OPTIMIZATION
ANNUAL COST     LOADING RATES(LB/HR-SQFT)
                  LIQUID       GAS         CAPITAL-$      HTUG(FT)     K(G)A     PACKING DEPTH        DIAMETER
   34609.         1000.        1812.        90452.        13.882      4.5000        27.3                8.89
   26049.         2500.        1414.        91001.         8.458      5.7631        16.6               10.07
   24338.         4000.        1189.        93385.         6.264      6.5420        12.3               10.98
   24206.         5500.        1031.        97028.         4.986      7.1303         9.8               11.79
   24756.         7000.         909.       101865.         4.121      7.6101         8.1               12.55
   24422.         6250.         959.        99664.         4.482      7.3807         8.8               12.22
   24196.         5500.        1023.        97330.         4.949      7.1303         9.7               11.83
   24133.         4750.        1006.        95278.         5.517      6.8536        10.8               11.43
   24302.         4000.        1181.        93597.         6.225      6.5429        12.2               11.02
   24196.         4375.        1141.        94276.         5.868      6.7031        11.5               11.21
   24144.         4750.        1100.        95155.         5.535      6.8536        10.9               11.41
   24148.         5125.        1062.        96128.         5.236      6.9057        10.3               11.62

          OPERATING CONDITIONS OF TOWER-CALCULATED
     THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
  TOWER DIAMETER     PACKING DEPTH     LOADING RATES      TOTAL FLOW RATES  -
       FEET              FEET          LBS/HR-SQFT      GAS(CFM)    LIQUID(GPM)
      11.62              10.3          1062.3    5125.    25000.      1080.

       PRESSURE DROP     FAN HORSEPOWER     PUMP HORSEPOWER
            5.1               36.3               11.1

        CHEMICAL CONSUMPTION
        CAUSTIC       CHLORINE
        LB/YEAR       LB/YEAR
         37836.        20800.

        CAPITAL COSTS FOR SCRUBBER SYSTEM
  TOWER    INTERNALS      PACKING     FAN     PUMP    MOTORS     TANKS     TOTAL
 56360.     6951.          17882.    1115.   2132.    2764.     8924.     96128.

           ANNUAL COST FOR SCRUBBER SYSTEM
      AMORTIZATION   POWER   MAINTENANCE   CHEMICAL        TOTAL    $/1000 CFM-HR
         12497.      4359.    1789.          5504.         24148.        .241
```

Table A5-7

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS
Case 7

```
                    NUMBER OF STAGES IN SCRUBBER IS 3.

                    TYPE OF PACKING AND ITS PROPERTIES
                    1 1/2 INTALOX SADDLES
                    POROSITY        AREA      EQUIVALENT      CONSTANTS FOR DELTAP
                                 SQFT/CUFT   DIAMETER(FT)       ALPHA      BETA
                       .810        52.8           .16            .130      .158


                    OPERATING CONDITIONS FOR TOWER

FLOW RATE   CONCENTRATION    HENRY    SCHMIDT NO    TEMPERATURE
   CFM        INLET  OUTLET                          DEGREES F
  25000.       500.    10.     0.         2.053            70.

                    UNIT COSTS FOR SCRUBBER SYSTEM
          POWER     MAINTENANCE       PACKING      AMORTIZATION
          $/KWH      $/SQRT(CFM)       $/CU-FT         FACTOR
           .025        8.000          8.200          .130

          INTERMEDIATE VALUES DURING OPTIMIZATION
ANNUAL COST     LOADING RATES(LB/HR-SQFT)
                LIQUID         GAS         CAPITAL-$      HTUG(FT)      K(G)A     PACKING DEPTH      DIAMETER
    35627.      1000.         1812.        111924.        13.882       4.5000       18.2                8.89
    27558.      2500.         1414.        107289.         9.458       5.7631       11.1               10.07
    26401.      4000.         1189.        111981.         6.264       6.5429        8.2               10.98
    26860.      5500.         1031.        118888.         4.986       7.1303        6.5               11.79
    26504.      4750.         1097.        115595.         5.518       6.8536        7.2               11.43
    26379.      4000.         1181.        112287.         6.225       6.5429        8.2               11.02
    26622.      3250.         1282.        109405.         7.146       6.1862        9.4               10.57
    26456.      3625.         1235.        110686.         6.671       6.3713        8.7               10.78
    26389.      4000.         1185.        112143.         6.244       6.5429        8.2               11.00
    26411.      4375.         1141.        113731.         5.865       6.7031        7.7               11.21


              OPERATING CONDITIONS OF TOWER-CALCULATED
          THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
     TOWER DIAMETER      PACKING DEPTH     LOADING RATES      TOTAL FLOW RATES
          FEET               FEET          LBS/HR-SQFT     GAS(CFM)    LIQUID(GPM)
         11.21                7.7         1140.7    4375.     25000.       850.

          PRESSURE DROP      FAN HORSEPOWER       PUMP HORSEPOWER
                6.1              43.6                 7.

              CHEMICAL CONSUMPTION
              CAUSTIC      CHLORINE
              LB/YEAR      LB/YEAR
               30418.       17119.

              CAPITAL COSTS FOR SCRUBBER SYSTEM
     TOWER       INTERNALS       PACKING     FAN      PUMP     MOTORS     TANKS      TOTAL
    66852.        9505.          18642.     1115.     2771.     3181.    11664.      113731.

                   ANNUAL COST FOR SCRUBBER SYSTEM
          AMORTIZATION    POWER    MAINTENANCE    CHEMICAL       TOTAL      $/1000 CFM-HR
               14785.     4967.    2191.          4468.          26411.          .264
6121.   6003  END OF PROGRAM
```

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Table A5-8

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS

Case 8

```
               NUMBER OF STAGES IN SCRUBBER IS 1.

               TYPE OF PACKING AND ITS PROPERTIES
               1 1/2 INTALOX SADDLES
               POROSITY       AREA      EQUIVALENT     CONSTANTS FOR DELTAP
                            SQFT/CUFT  DIAMETER(FT)       ALPHA     BETA
                  .810        52.0         .16             .130     .160


               OPERATING CONDITIONS FOR TOWER

  FLOW RATE   CONCENTRATION   HENRY   SCHMIDT NO   TEMPERATURE
     CFM      INLET  OUTLET                          DEGREES F
   25000.     2000.   20.       0.       2.053           70.

               UNIT COSTS FOR SCRUBBER SYSTEM
        POWER     MAINTENANCE      PACKING     AMORTIZATION
        $/KWH     $/SQFT(CFM)      $/CU-FT        FACTOR
         .025        8.000          9.300          .130

        INTERMEDIATE VALUES DURING OPTIMIZATION
 ANNUAL COST     LOADING RATES(LB/HR-SQFT)
                    LIQUID      GAS        CAPITAL-$      HTU(FT)     K(G)A     PACKING DEPTH     DIAMETER
   62916.           1000.      1812.        96660.        13.002      4.6868        67.0             8.80
   52332.           2500.      1414.        84505.         9.458      5.7671        30.0            10.07
   49624.           4000.      1180.        82223.         6.261      6.6420        28.0            10.98
   48701.           5500.      1031.        82301.         4.086      7.1303        23.0            11.70
   48506.           7000.       960.        83565.         4.321      7.6101        19.0            12.55
   48705.           8500.       811.        85607.         3.486      8.0107        16.3            13.30
   48557.           7750.       850.        84763.         3.747      7.8221        17.3            12.99
   48486.           7000.       901.        83803.         4.085      7.6101        18.8            12.61


              OPERATING CONDITIONS OF TOWER-CALCULATED
         THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
   TOWER DIAMETER    PACKING DEPTH    LOADING RATES      TOTAL FLOW RATES
       FEET              FEET         LBS/HR-SQFT     GAS(CFM)    LIQUID(GPM)
      12.61              18.8         901.5   7000.    25000.       1730.

        PRESSURE DROP     FAN HORSEPOWER      PUMP HORSEPOWER
               4.0             28.6                25.3

             CHEMICAL CONSUMPTION
             CAUSTIC       CHLORINE
             LB/YEAR       LB/YEAR
             202146.        137697.

             CAPITAL COSTS FOR SCRUBBER SYSTEM
   TOWER     INTERNALS     PACKING     FAN     PUMP      MOTORS      TANKS       TOTAL
  60383.      4303.         10251.    1115.    1435.      2370.      5077.       83803.

                  ANNUAL COST FOR SCRUBBER SYSTEM
          AMORTIZATION    POWER   MAINTENANCE   CHEMICAL        TOTAL     $/1000 CFM-HR
             10894.       4030.    1255.          32307.        48486.        .155
```

Table A5-9

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS
Case 9

```
                    NUMBER OF STAGES IN SCRUBBER IS 2.

                    TYPE OF PACKING AND ITS PROPERTIES
                    1 1/2 INTALOX SADDLES
                    POROSITY         AREA      EQUIVALENT      CONSTANTS FOR DELTAP
                                  SQFT/CUFT   DIAMETER(FT)       ALPHA     BETA
                       .810         52.0          .16             .130      .150


                    OPERATING CONDITIONS FOR TOWER

  FLOW RATE    CONCENTRATION    HENRY    SCHMIDT NO    TEMPERATURE
     CFM       INLET  OUTLET                            DEGREES F
   25000.      2000.    20.      0.          2.053           70.

                    UNIT COSTS FOR SCRUBBER SYSTEM
          POWER      MAINTENANCE      PACKING      AMORTIZATION
          $/KWH      $/SQFT(CFM)      $/CU-FT         FACTOR
           .025        8.000          8.200          .130

          INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST      LOADING RATES(LB/HR-SQFT)
                     LIQUID         GAS          CAPITAL-$       HTUG(FT)      K(G)A     PACKING DEPTH        DIAMETER
     53184.          1000.         1812.         110337.         13.882       4.5000        32.0                 8.80
     43030.          2500.         1416.         100762.          8.658       5.7631        19.5                10.02
     40846.          4000.         1188.         101472.          6.751       6.5420        14.4                10.98
     40402.          5500.         1031.         104646.          4.996       7.1303        11.5                11.79
     40910.          7000.          900.         109154.          4.331       7.6101         9.5                12.55
     40631.          6250.          950.         107100.          4.692       7.3867        10.7                12.22
     40474.          5500.         1023.         104052.          4.940       7.1303        11.4                11.83
     40503.          4750.         1096.         103110.          5.517       6.9536        12.7                11.43


                 OPERATING CONDITIONS OF TOWER-CALCULATED
              THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
       TOWER DIAMETER      PACKING DEPTH      LOADING RATES      TOTAL FLOW RATES
           FEET                FEET          LBS/HR-SQFT     GAS(CFM)    LIQUID(GPM)
          11.43                12.7         1096.5    4750.     25000.        970.

          PRESSURE DROP      FAN HORSEPOWER      PUMP HORSEPOWER
                6.4               46.0                11.1

                 CHEMICAL CONSUMPTION
                 CAUSTIC      CHLORINE
                 LB/YEAR      LB/YEAR
                 129143.        84014.

                 CAPITAL COSTS FOR SCRUBBER SYSTEM
       TOWER     INTERNALS      PACKING      FAN      PUMP      MOTORS      TANKS      TOTAL
      60562.      6671.         21376.      1115.     2002.      3010.      8365.     103110.

                    ANNUAL COST FOR SCRUBBER SYSTEM
               AMORTIZATION    POWER   MAINTENANCE    CHEMICAL       TOTAL     $/1000 CFM-HP
                  13404.       5091.    1789.          20219.        40503.        .405
```

Table A5-10

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS
Case 10

```
                    NUMBER OF STAGES IN SCRUBBER IS 3.

                    TYPE OF PACKING AND ITS PROPERTIES
                    1 1/2 INTALOX SADDLES
                    POROSITY        AREA      EQUIVALENT      CONSTANTS FOR DELTAP
                                 SQFT/CUFT   DIAMETER(FT)       ALPHA     BETA
                       .810        52.0           .16            .130      .150


                    OPERATING CONDITIONS FOR TOWER

  FLOW RATE   CONCENTRATION    HENRY   SCHMIDT NO   TEMPERATURE
     CFM       INLET  OUTLET                          DEGREES F
   25000.      2000.    20.     0.       2.053          70.

                    UNIT COSTS FOR SCRUBBER SYSTEM
           POWER    MAINTENANCE       PACKING    AMORTIZATION
           $/KWH    $/SQRT(CFM)       $/CU-FT       FACTOR
            .025       8.000          8.200        .130

           INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST     LOADING RATES(LB/HR-SQFT)
                      LIQUID       GAS        CAPITAL-$      HTUG(FT)      K(G)A     PACKING DEPTH        DIAMETER
     51854.           1000.       1812.       123478.        13.982       4.5000        21.3               8.89
     42149.           2500.       1414.       116666.         8.458       5.7631        13.0              10.07
     40504.           4000.       1180.       120513.         6.264       6.5429         9.6              10.98
     40733.           5500.       1031.       126001.         4.986       7.1303         7.7              11.79
     40464.           4750.       1097.       123845.         5.518       6.8536         8.5              11.43
     40471.           4000.       1181.       120822.         6.225       6.5429         9.6              11.02


                OPERATING CONDITIONS OF TOWER-CALCULATED
           THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
      TOWER DIAMETER      PACKING DEPTH      LOADING RATES      TOTAL FLOW RATES
          FEET                FEET          LBS/HR-SQFT     GAS(CFM)    LIQUID(GPM)
         11.02                9.6          1181.2   4000.      25000.        758.

           PRESSURE DROP      FAN HORSEPOWER       PUMP HORSEPOWER
                 7.9               56.1                  7.5

                CHEMICAL CONSUMPTION
                CAUSTIC       CHLORINE
                LB/YEAR       LB/YEAR
                107122.         69118.

                CAPITAL COSTS FOR SCRUBBER SYSTEM
     TOWER      INTERNALS      PACKING      FAN      PUMP     MOTORS      TANKS        TOTAL
    71341.       9084.          22422.     1115.     2575.     3461.    10824.        120822.

                     ANNUAL COST FOR SCRUBBER SYSTEM
              AMORTIZATION   POWER   MAINTENANCE    CHEMICAL       TOTAL     $/1000 CFM-HR
                 15707.      5865.    2191.          16708.       40471.          .405

  6121.   6003  END OF PROGRAM
```

Table A5-11

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS
Case 11

```
            NUMBER OF STAGES IN SCRUBBER IS 1.

            TYPE OF PACKING AND ITS PROPERTIES
            1 1/2 INTALOX SADDLES
            POROSITY        AREA     EQUIVALENT      CONSTANTS FOR DELTAP
                         SQFT/CUFT   DIAMETER(FT)       ALPHA     BETA
              .810        52.0          .16              .130     .150


            OPERATING CONDITIONS FOR TOWER

 FLOW RATE   CONCENTRATION   HENRY   SCHMIDT NO   TEMPERATURE
    CFM      INLET  OUTLET                          DEGREES F
  50000.      500.   10.      0.        2.053          70.

            UNIT COSTS FOR SCRUBBER SYSTEM
      POWER     MAINTENANCE      PACKING    AMORTIZATION
      $/KWH     $/SQRT(CFM)      $/CU-FT       FACTOR
       .025        8.000          8.200         .130

      INTERMEDIATE VALUES DURING OPTIMIZATION
 ANNUAL COST    LOADING RATES(LB/HR-SQFT)
                 LIQUID       GAS        CAPITAL-$      HTUG(FT)     K(G)A     PACKING DEPTH       DIAMETER
                                                         13.882      4.5000        54.3              12.58
   69317.        1000.       1812.       161729.          8.458      5.7631        33.1              14.24
   51890.        2500.       1414.       145217.          6.264      6.5429        24.5              15.53
   47412.        4000.       1189.       141971.          4.986      7.1303        19.5              16.67
   45966.        5500.       1031.       142651.          4.121      7.6101        16.1              17.75
   45765.        7000.        909.       145339.          3.486      8.0197        13.6              18.80
   46247.        8500.        811.       149371.          3.747      7.8221        14.7              18.36
   45930.        7750.        850.       147712.          4.085      7.6101        16.0              17.83
   45739.        7000.        901.       145799.          4.480      7.3807        17.5              17.29
   45714.        6250.        959.       144197.

            OPERATING CONDITIONS OF TOWER-CALCULATED
        THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
    TOWER DIAMETER     PACKING DEPTH     LOADING RATES      TOTAL FLOW RATES
         FEET              FEET          LBS/HR-SQFT     GAS(CFM)    LIQUID(GPM)
        17.29              17.5          958.9   6250.     50000.       2919.

        PRESSURE DROP      FAN HORSEPOWER       PUMP HORSEPOWER
              3.9              56.0                  40.6

            CHEMICAL CONSUMPTION
            CAUSTIC      CHLORINE
            LB/YEAR      LB/YEAR
            123340.        68054.

            CAPITAL COSTS FOR SCRUBBER SYSTEM
  TOWER     INTERNALS     PACKING     FAN      PUMP      MOTORS      TANKS       TOTAL
  85280.     9777.         33724.     1866.    1940.     3510.       8101.      144197.

              ANNUAL COST FOR SCRUBBER SYSTEM
       AMORTIZATION    POWER   MAINTENANCE   CHEMICAL        TOTAL     $/1000 CFM-HR
          18746.       7210.     1789.        17970.         45714.         .229
```

Table A5-12

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS
Case 12

```
                    NUMBER OF STAGES IN SCRUBBER IS 2.

                    TYPE OF PACKING AND ITS PROPERTIES
                    1 1/2 INTALOX SADDLES
                    POROSITY        AREA      EQUIVALENT     CONSTANTS FOR DELTAP
                                 SQFT/CUFT   DIAMETER(FT)      ALPHA     BETA
                       .810        52.0          .16            .130      .150


                    OPERATING CONDITIONS FOR TOWER

  FLOW RATE    CONCENTRATION   HENRY   SCHMIDT NO    TEMPERATURE
     CFM        INLET  OUTLET                         DEGREES F
   50000.        500.    10.     0.         2.053           70.

                    UNIT COSTS FOR SCRUBBER SYSTEM
          POWER     MAINTENANCE      PACKING     AMORTIZATION
          $/KWH      $/SQRT(CFM)      $/CU-FT        FACTOR
           .025        8.000         8.200         .130

          INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST     LOADING RATES(LB/HR-SQFT)
                  LIQUID       GAS         CAPITAL-$      HTUG(FT)      K(G)A    PACKING DEPTH       DIAMETER
      66621.      1000.       1812.        186004.       13.982      4.5000      27.3               12.58
      50008.      2500.       1414.        175778.        8.458      5.7631      16.6               14.24
      46406.      4000.       1189.        178057.        6.264      6.5429      12.3               15.53
      46115.      5500.       1031.        184453.        4.986      7.1303       9.8               16.67
      47088.      7000.        909.        193135.        4.121      7.6101       8.1               17.75
      46484.      6250.        959.        189231.        4.482      7.3807       8.8               17.29
      46095.      5500.       1023.        185052.        4.949      7.1303       9.7               16.74
      46030.      4750.       1096.        181411.        5.517      6.8536      10.8               16.17


               OPERATING CONDITIONS OF TOWER-CALCULATED
           THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
      TOWER DIAMETER      PACKING DEPTH      LOADING RATES      TOTAL FLOW RATES
           FEET                FEET          LBS/HR-SQFT     GAS(CFM)    LIQUID(GPM)
          16.17                10.8         1096.5    4750.     50000.      1940.

           PRESSURE DROP      FAN HORSEPOWER       PUMP HORSEPOWER
                   5.5             78.5                  20.4

               CHEMICAL CONSUMPTION
               CAUSTIC       CHLORINE
               LB/YEAR       LB/YEAR
                75672.          41600.

               CAPITAL COSTS FOR SCRUBBER SYSTEM
      TOWER       INTERNALS        PACKING       FAN      PUMP      MOTORS      TANKS       TOTAL
    106511.       16426.           36505.       1866.     3008.     4414.      12680.      181411.

                    ANNUAL COST FOR SCRUBBER SYSTEM
            AMORTIZATION    POWER    MAINTENANCE    CHEMICAL        TOTAL     $/1000 CFM-HR
               23583.       8908.    2530.          11008.         46030.         .230

  6121.   6003  END OF PROGRAM
```

Table A5-13

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS
Case 13

```
                NUMBER OF STAGES IN SCRUBBER IS 2.

                TYPE OF PACKING AND ITS PROPERTIES
                1 1/2 INTALOX SADDLES
                POROSITY       AREA       EQUIVALENT      CONSTANTS FOR DELTAP
                            SQFT/CUFT   DIAMETER(FT)       ALPHA     BETA
                   .810        52.0          .16            .130     .150


                 OPERATING CONDITIONS FOR TOWER

 FLOW RATE    CONCENTRATION    HENRY    SCHMIDT NO    TEMPERATURE
    CFM       INLET  OUTLET                           DEGREES F
  50000.      2000.    20.      0.          2.053          70.

                 UNIT COSTS FOR SCRUBBER SYSTEM
           POWER      MAINTENANCE      PACKING      AMORTIZATION
           $/KWH      $/SQRT(CFM)      $/CU-FT         FACTOR
            .025         8.000          8.200          .130

            INTERMEDIATE VALUES DURING OPTIMIZATION
 ANNUAL COST      LOADING RATES(LB/HR-SQFT)
                   LIQUID      GAS        CAPITAL-$      HTUG(FT)     K(G)A      PACKING DEPTH       DIAMETER
                                                                                                      12.58
   103625.         1000.      1812.       207633.         13.882     4.5000         32.0             14.24
    83888.         2500.      1414.       192876.          8.458     5.7631         19.5             15.53
    79438.         4000.      1189.       193661.          6.264     6.5429         14.4             16.67
    78618.         5500.      1031.       199150.          4.986     7.1303         11.5             17.75
    79345.         7000.       900.       207196.          4.121     7.6101          9.5             17.29
    78832.         6250.       959.       203594.          4.482     7.3807         10.3             16.74
    78580.         5500.      1023.       199757.          4.049     7.1303         11.4             16.17
    78608.         4750.      1096.       196523.          5.517     6.8536         12.7             16.43
    78609.         5125.      1062.       197790.          5.236     6.9957         12.1


            OPERATING CONDITIONS OF TOWER-CALCULATED
         THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
   TOWER DIAMETER     PACKING DEPTH      LOADING RATES        TOTAL FLOW RATES
       FEET               FEET           LBS/HR-SQFT       GAS(CFM)    LIQUID(GPM)
      16.43               12.1           1062.2    5125.    50000.       2161.

         PRESSURE DROP      FAN HORSEPOWER       PUMP HORSEPOWER
              5.0               84.0                 24.1

            CHEMICAL CONSUMPTION
            CAUSTIC       CHLORINE
            LB/YEAR       LB/YEAR
            258287.        168028.

            CAPITAL COSTS FOR SCRUBBER SYSTEM
   TOWER    INTERNALS      PACKING      FAN      PUMP      MOTORS      TANKS       TOTAL
  115413.    17118.         41885.     1866.     3206.     4775.     13526.     197790.

                 ANNUAL COST FOR SCRUBBER SYSTEM
          AMORTIZATION    POWER   MAINTENANCE     CHEMICAL       TOTAL      $/1000 CFM-HR
             25713.       9929.     2530.          40437.        78609.          .793
```

Table A5-14

DESIGN AND COST CALCULATIONS FOR PACKED TOWERS
Case 14

```
                NUMBER OF STAGES IN SCRUBBER IS 3.

                TYPE OF PACKING AND ITS PROPERTIES
                1 1/2 INTALOX SADDLES
                POROSITY       AREA      EQUIVALENT      CONSTANTS FOR DELTAP
                             SQFT/CUFT  DIAMETER(FT)       ALPHA      BETA
                   .810        52.0          .10            .130      .150

                OPERATING CONDITIONS FOR TOWER

FLOW RATE   CONCENTRATION   HENRY   SCHMIDT NO   TEMPERATURE
   CFM      INLET  OUTLET                        DEGREES F
 50000.     2000.    20.     0.        2.053          70.

                UNIT COSTS FOR SCRUBBER SYSTEM
         POWER     MAINTENANCE     PACKING     AMORTIZATION
         $/KWH     $/SQRT(CFM)     $/CU-FT        FACTOR
          .025       8.000          8.200        .130

            INTERMEDIATE VALUES DURING OPTIMIZATION
ANNUAL COST     LOADING RATES(LB/HR-SQFT)
                LIQUID      GAS        CAPITAL-$      HTUG(FT)     K(G)A     PACKING DEPTH      DIAMETER
  100525.       1000.       1812.      232350.        13.882       4.5000      21.3              12.58
   81698.       2500.       1414.      223201.         8.458       5.7631      13.0              14.24
   78254.       4000.       1189.      229705.         6.264       6.5420       9.6              15.53
   78527.       5500.       1031.      241064.         4.996       7.1303       7.7              16.67
   78083.       4750.       1097.      235673.         5.518       6.8536       8.5              16.17
   78186.       4000.       1181.      230320.         6.225       6.5420       9.6              15.58

              OPERATING CONDITIONS OF TOWER-CALCULATED
          THE MATERIAL OF CONSTRUCTION IS FIBERGLASS(FRP)
      TOWER DIAMETER      PACKING DEPTH      LOADING RATES      TOTAL FLOW RATES
          FEET                 FEET         LBS/HR-SQFT     GAS(CFM)    LIQUID(GPM)
         15.58                 9.6        1181.2   4000.     50000.      1517.

          PRESSURE DROP      FAN HORSEPOWER      PUMP HORSEPOWER
                7.0             112.2                 15.0

              CHEMICAL CONSUMPTION
              CAUSTIC       CHLORINE
              LB/YEAR       LB/YEAR
              214245.        138237.

              CAPITAL COSTS FOR SCRUBBER SYSTEM
     TOWER     INTERNALS      PACKING     FAN      PUMP      MOTORS      TANKS       TOTAL
   135454.     22366.          44843.    1866.    3878.     5506.     16407.       230320.

                    ANNUAL COST FOR SCRUBBER SYSTEM
           AMORTIZATION   POWER   MAINTENANCE   CHEMICAL        TOTAL     $/1000 CFM-HR
              29942.      11729.   3098.          33417.        78186.          .391

6121.    6003  END OF PROGRAM
```

Table A5-15

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS

Case 1

```
                   CHAMBER                  TOTAL
   NOZZLES/SQ FT   LENGTH   UNITS/SERIES    LENGTH   NOZZLE PSI
         6.0         8.0          1.0       20.0        15.0
GPM/NOZZLE
     1.000     2.000     3.000     4.000     5.000

                    UNIT COSTS FOR SCRUBBER SYSTEM
POWER     MAINTENANCE     NOZZLES     AMORTIZATION
$/KWH     $/SQRT(CFM)      $ EA          FACTOR
  .025        8.000        5.000         .130

FLOW RATE   CONCENTRATION   HENRY   SCHMIDT NO   TEMPERATURE
   CFM      INLET  OUTLET                         DEGREES F
  25000.     500.   10.       0.          0.            70.

          INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST  CAPITAL  TIM-SEC  HEIGHT  GPM/NOZ  FT2/FT3  NO    N1
     18351.     49461.     1.3     8.2     1.0      9.6 2051449 1912313
      18351.
     17860.     43471.      .9     6.8     2.0     11.7 1963302 1752764
      17860.
     17722.     40775.      .7     6.0     3.0     13.1 1913506 1648077
      17722.
     17690.     39177.      .6     5.6     4.0     14.1 1878943 1567999
      17690.
     17702.     38101.      .5     5.2     5.0     15.0 1852564 1502437
     17690.     39177.      .6     5.6     4.0     14.1 1878943 1567999
      17690.


               OPERATING CONDITIONS OF TOWER-CALCULATED
          THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
     SCRUBBER WIDTH     SCRUBBER HEIGHT     TOTAL FLOW RATES
          FEET                FEET        GAS(CFM)    LIQUID(GPM)
             5.6              5.6        25000.0            745.6

     NOZZLES/BANK     BANKS/UNIT     DDROP UM     UNITS/SERIES
           186.            1.            461.             1.

          PRESSURE DROP     FAN HORSEPOWER     PUMP HORSEPOWER
                  1.500       10.705             20.756


               CHEMICAL CONSUMPTION
               CAUSTIC      CHLORINE
               LB/YEAR      LB/YEAR
                61670.        34027.


               CAPITAL COSTS FOR SCRUBBER SYSTEM
 SHELL     NOZZLES     FAN     PUMP     MOTORS     TANKS     EXTERNALS     TOTAL
17711.      932.       519.     883.    1640.       3929.     13563.        39177.

                    ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION   POWER  MAINTENANCE    CHEMICALS   TOTAL   $/1000CFM-HR
     5093.      2347.   1265.          8985.    17690.        .177
```

Table A5-16

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 2

```
                          CHAMBER                           TOTAL
     NOZZLES/SQ FT        LENGTH      UNITS/SERIES          LENGTH      NOZZLE PSI
           6.0             16.0            1.0               28.0          15.0
  GPM/NOZZLE
        1.000         2.000        3.000        4.000        5.000

                         UNIT COSTS FOR SCRUBBER SYSTEM
  POWER        MAINTENANCE        NOZZLES        AMORTIZATION
  $/KWH        $/SQRT(CFM)         $ EA             FACTOR
   .025           8.000           5.000              .130

  FLOW RATE     CONCENTRATION      HENRY     SCHMIDT NO     TEMPERATURE
    CFM         INLET   OUTLET                                DEGREES F
   25000.        500.     10.        0.            0.                70.

                   INTERMEDIATE VALUES DURING OPTIMIZATION
    ANNUAL COST    CAPITAL    TIM-SEC    HEIGHT    GPM/NOZ    FT2/FT3   NO      N1
        18459.      51754.       2.0        7.3        1.0        7.6 1628217 1491496
         18459.
        17820.      45094.       1.4        6.0        2.0        9.3 1558256 1353433
         17820.
        17591.      42047.       1.1        5.4        3.0       10.4 1518733 1262549
         17591.
        17492.      40214.        .9        5.0        4.0       11.2 1491301 1193189
         17492.
        17449.      38964.        .8        4.7        5.0       11.9 1470364 1136641
         17449.
        17449.      38964.        .8        4.7        5.0       11.9 1470364 1136641
         17449.


                      OPERATING CONDITIONS OF TOWER-CALCULATED
                 THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
        SCRUBBER WIDTH        SCRUBBER HEIGHT        TOTAL FLOW RATES
             FEET                   FEET            GAS(CFM)     LIQUID(GPM)
              4.7                    4.7            25000.0             653.8

        NOZZLES/BANK       BANKS/UNIT        DDROP UM        UNITS/SERIES
            131.               1.               478.                1.

             PRESSURE DROP        FAN HORSEPOWER        PUMP HORSEPOWER
                    1.500            10.705               17.902


                      CHEMICAL CONSUMPTION
                      CAUSTIC       CHLORINE
                      LB/YEAR       LB/YEAR
                       61670.         34027.


                      CAPITAL COSTS FOR SCRUBBER SYSTEM
  SHELL       NOZZLES       FAN       PUMP       MOTORS       TANKS       EXTERNALS       TOTAL
  18232.       654.         519.       820.       1546.        3631.        13563.         38964.

                           ANNUAL COST FOR SCRUBBER SYSTEM
  AMORTIZATION     POWER    MAINTENANCE      CHEMICALS      TOTAL      $/1000CFM-HR
       5065.        2134.    1265.               8985.      17449.           .174
```

Table A5-17

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 3

```
                   CHAMBER                        TOTAL
   NOZZLES/SQ FT   LENGTH    UNITS/SERIES         LENGTH    NOZZLE PSI
         6.0         8.0           2.0            36.0         15.0
GPM/NOZZLE
     1.000     2.000     3.000     4.000     5.000

                    UNIT COSTS FOR SCRUBBER SYSTEM
POWER     MAINTENANCE      NOZZLES      AMORTIZATION
$/KWH     $/SQRT(CFM)       $ EA           FACTOR
 .025        8.000         5.000           .130

FLOW RATE   CONCENTRATION    HENRY    SCHMIDT NO    TEMPERATURE
  CFM       INLET  OUTLET                            DEGREES F
 25000.      500.   10.        0.         0.               70.

              INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST   CAPITAL   TIM-SEC  HEIGHT  GPM/NOZ   FT2/FT3  NO     N1
     17667.      59273.      1.6     6.5     1.0       6.1 1296748 1260114
      17667.
     17175.      52721.      1.1     5.4     2.0       7.4 1241029 1184193
      17175.
     17067.      49845.       .9     4.8     3.0       8.3 1209552 1136421
      17067.
     17070.      48178.       .8     4.4     4.0       8.9 1187704 1100504
     17118.      47083.       .7     4.2     5.0       9.5 1171030 1071278
     17067.      49845.       .9     4.8     3.0       8.3 1209552 1136421
      17067.


                  OPERATING CONDITIONS OF TOWER-CALCULATED
             THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
     SCRUBBER WIDTH      SCRUBBER HEIGHT      TOTAL FLOW RATES
         FEET                  FEET          GAS(CFM)     LIQUID(GPM)
          4.8                  4.8           25000.0           414.5

     NOZZLES/BANK      BANKS/UNIT      DDROP UM      UNITS/SERIES
         138.              1.            439.               2.

          PRESSURE DROP      FAN HORSEPOWER      PUMP HORSEPOWER
                3.000          21.409             11.376

               CHEMICAL CONSUMPTION
               CAUSTIC      CHLORINE
               LB/YEAR      LB/YEAR
                37836.        20800.


               CAPITAL COSTS FOR SCRUBBER SYSTEM
 SHELL      NOZZLES      FAN      PUMP      MOTORS      TANKS      EXTERNALS      TOTAL
22145.      1382.        519.     1222.     2356.        5525.      16697.        49845.

                  ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION   POWER   MAINTENANCE     CHEMICALS   TOTAL    $/1000CFM-HR
    6480.      3294.    1789.            5504.     17067.        .171
```

Table A5-18

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 4

```
                    CHAMBER                            TOTAL
   NOZZLES/SQ FT    LENGTH    UNITS/SERIES     LENGTH    NOZZLE PSI
        6.0          16.0          2.0          52.0         15.0
GPM/NOZZLE
     1.000      2.000      3.000      4.000      5.000

                    UNIT COSTS FOR SCRUBBER SYSTEM
POWER      MAINTENANCE      NOZZLES      AMORTIZATION
$/KWH      $/SQRT(CFM)       $ EA           FACTOR
  .025        8.000          5.000           .130

FLOW RATE    CONCENTRATION    HENRY    SCHMIDT NO    TEMPERATURE
  CFM        INLET  OUTLET                              DEGREES F
 25000.       500.   10.        0.           0.               70.

          INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST   CAPITAL   TIM-SEC   HEIGHT   GPM/NOZ   FT2/FT3   NO     N1
     17740.      61616.     2.6       5.8      1.0       4.8 1029217  992852
     17740.
     17070.      54283.     1.8       4.8      2.0       5.9  984994  928829
     17070.
     16853.      50989.     1.4       4.3      3.0       6.6  960011  888014
     16853.
     16773.      49041.     1.2       3.9      4.0       7.1  942671  857106
     16773.
     16754.      47733.     1.1       3.7      5.0       7.5  929436  831848
     16754.
     16754.      47733.     1.1       3.7      5.0       7.5  929436  831848
     16754.


               OPERATING CONDITIONS OF TOWER-CALCULATED
          THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
     SCRUBBER WIDTH      SCRUBBER HEIGHT      TOTAL FLOW RATES
          FEET                 FEET          GAS(CFM)     LIQUID(GPM)
           3.7                  3.7          25000.0         413.3

     NOZZLES/BANK      BANKS/UNIT      DDROP UM      UNITS/SERIES
          83.               1.            478.              2.

          PRESSURE DROP      FAN HORSEPOWER      PUMP HORSEPOWER
                3.000          21.409              11.116


               CHEMICAL CONSUMPTION
               CAUSTIC       CHLORINE
               LB/YEAR       LB/YEAR
                37836.         20800.


               CAPITAL COSTS FOR SCRUBBER SYSTEM
 SHELL     NOZZLES     FAN     PUMP     MOTORS      TANKS     EXTERNALS      TOTAL
20621.      827.       519.    1220.    2335.       5515.      16697.        47733.

                    ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION    POWER   MAINTENANCE   CHEMICALS   TOTAL    $/1000CFM-HR
    6205.       3256.    1789.           5504.    16754.         .168
```

Table A5-19

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 5

```
                     CHAMBER                        TOTAL
   NOZZLES/SQ FT     LENGTH    UNITS/SERIES        LENGTH    NOZZLE PSI
        6.0           16.0         2.0              52.0        25.0
GPM/NOZZLE
    2.000       3.000       4.000       5.000       6.000

                      UNIT COSTS FOR SCRUBBER SYSTEM
POWER      MAINTENANCE      NOZZLES       AMORTIZATION
$/KWH      $/SQRT(CFM)        $ EA           FACTOR
  .025        8.000          5.000       .    .130

FLOW RATE    CONCENTRATION    HENRY    SCHMIDT NO    TEMPERATURE
   CFM       INLET  OUTLET                             DEGREES F
  25000.      500.   10.        0.          0.              70.

            INTERMEDIATE VALUES DURING OPTIMIZATION
   ANNUAL COST   CAPITAL   TIM-SEC   HEIGHT   GPM/NOZ   FT2/FT3  NO   N1
      17222.      52753.      1.6      4.6      2.0      6.1 1300300 1228882
      17222.
      17102.      49663.      1.3      4.1      3.0      6.8 1267320 1175707
      17102.
      17098.      47841.      1.1      3.8      4.0      7.4 1244429 1135484
      17098.
      17141.      46623.      1.0      3.6      5.0      7.9 1226958 1102635
      17207.      45747.       .9      3.4      6.0      8.3 1212866 1074622
      17098.      47841.      1.1      3.8      4.0      7.4 1244429 1135484
      17098.


                OPERATING CONDITIONS OF TOWER-CALCULATED
            THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
       SCRUBBER WIDTH      SCRUBBER HEIGHT      TOTAL FLOW RATES
           FEET                  FEET          GAS(CFM)    LIQUID(GPM)
            3.8                  3.8           25000.0           345.5

       NOZZLES/BANK       BANKS/UNIT       DDROP UM       UNITS/SERIES
            86.               1.              409.               2.

            PRESSURE DROP       FAN HORSEPOWER        PUMP HORSEPOWER
                   3.000          21.409                13.326


                CHEMICAL CONSUMPTION
                CAUSTIC      CHLORINE
                LB/YEAR      LB/YEAR
                 37836.        20800.


                CAPITAL COSTS FOR SCRUBBER SYSTEM
 SHELL      NOZZLES      FAN     PUMP     MOTORS       TANKS      EXTERNALS        TOTAL
21203.      864.        519.    1101.    2505.        4953.      16697.           47841.

                     ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION    POWER   MAINTENANCE    CHEMICALS   TOTAL    $/1000CFM-HR
    6219.       3585.    1789.           5504.    17098.         .171
```

Table A5-20

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 6

```
                        CHAMBER                            TOTAL
   NOZZLES/SQ FT        LENGTH    UNITS/SERIES             LENGTH    NOZZLE PSI
        6.0               8.0           3.0                 52.0        15.0
GPM/NOZZLE
     1.000       2.000       3.000       4.000       5.000

                          UNIT COSTS FOR SCRUBBER SYSTEM
POWER       MAINTENANCE        NOZZLES       AMORTIZATION
$/KWH       $/SQRT(CFM)         $ EA            FACTOR
  .025          8.000           5.000            .130

FLOW RATE    CONCENTRATION     HENRY     SCHMIDT NO     TEMPERATURE
   CFM       INLET  OUTLET                               DEGREES F
  25000.      500.   10.         0.            0.                70.

              INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST   CAPITAL   TIM-SEC   HEIGHT   GPM/NOZ   FT2/FT3  NO    N1
      19085.      67871.      1.9      5.7      1.0       4.6  988881  972441
       19085.
      18554.      60644.      1.3      4.7      2.0       5.6  946391  920693
       18554.
      18451.      57514.      1.0      4.2      3.0       6.3  922387  889114
       18451.
      18468.      55724.       .9      3.9      4.0       6.9  905726  865830
      18534.      54564.       .8      3.6      5.0       7.3  893011  847138
      18451.      57514.      1.0      4.2      3.0       6.3  922387  889114
       18451.


                   OPERATING CONDITIONS OF TOWER-CALCULATED
               THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
    SCRUBBER WIDTH       SCRUBBER HEIGHT       TOTAL FLOW RATES
         FEET                  FEET           GAS(CFM)     LIQUID(GPM)
          4.2                   4.2           25000.0          316.1

    NOZZLES/BANK         BANKS/UNIT        DDROP UM        UNITS/SERIES
         105.                 1.              439.                3.

               PRESSURE DROP       FAN HORSEPOWER        PUMP HORSEPOWER
                   4.500              32.114                 8.578


                     CHEMICAL CONSUMPTION
                     CAUSTIC       CHLORINE
                     LB/YEAR       LB/YEAR
                      30418.         17110.


                     CAPITAL COSTS FOR SCRUBBER SYSTEM
 SHELL      NOZZLES      FAN      PUMP      MOTORS      TANKS      EXTERNALS        TOTAL
24974.      1580.       519.     1544.      2996.        7043.      18857.          57514.

                         ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION    POWER    MAINTENANCE     CHEMICALS     TOTAL     $/1000CFM-HR
    7477.       4315.    2191.             4468.      18451.         .185
```

Table A5-21

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 7

```
                        CHAMBER                            TOTAL
   NOZZLES/SQ FT        LENGTH     UNITS/SERIES            LENGTH    NOZZLE PSI
          6.0             8.0            1.0               20.0         15.0
GPM/NOZZLE
     1.000       2.000       3.000       4.000       5.000

                   UNIT COSTS FOR SCRUBBER SYSTEM
POWER      MAINTENANCE       NOZZLES      AMORTIZATION
$/KWH      $/SQRT(CFM)        $ EA           FACTOR
  .025        8.000          5.000           .130

FLOW RATE    CONCENTRATION     HENRY     SCHMIDT NO     TEMPERATURE
   CFM       INLET  OUTLET                               DEGREES F
  25000.     2000.   20.        0.            0.               70.

              INTERMEDIATE VALUES DURING OPTIMIZATION
    ANNUAL COST   CAPITAL   TIM-SEC   HEIGHT   GPM/NOZ    FT2/FT3   NO      N1
        42112.     52005.      1.4      8.6       1.0       10.7 2287139 2097453
        42112.
        41596.     45560.      1.0      7.1       2.0       13.0 2188865 1904514
        41596.
        41457.     42660.       .8      6.4       3.0       14.6 2133348 1777514
        41457.
        41429.     40940.       .7      5.9       4.0       15.8 2094814 1680570
        41429.
        41448.     39783.       .6      5.5       5.0       16.8 2065405 1601508
        41429.     40940.       .7      5.9       4.0       15.8 2094814 1680570
        41429.


                 OPERATING CONDITIONS OF TOWER-CALCULATED
             THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
        SCRUBBER WIDTH      SCRUBBER HEIGHT     TOTAL FLOW RATES
             FEET                 FEET          GAS(CFM)     LIQUID(GPM)
              5.9                 5.9           25000.0           831.3

        NOZZLES/BANK      BANKS/UNIT       DDROP UM      UNITS/SERIES
            208.               1.            461.               1.

             PRESSURE DROP     FAN HORSEPOWER     PUMP HORSEPOWER
                    1.500        10.705             23.272


                 CHEMICAL CONSUMPTION
                 CAUSTIC      CHLORINE
                 LB/YEAR      LB/YEAR
                 202146.       137497.


                 CAPITAL COSTS FOR SCRUBBER SYSTEM
SHELL     NOZZLES     FAN     PUMP     MOTORS      TANKS      EXTERNALS        TOTAL
18967.    1039.       519.    939.     1720.       4194.      13563.          40940.

                    ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION     POWER   MAINTENANCE    CHEMICALS   TOTAL    $/1000CFM-HR
    5322.        2535.   1265.           32307.     41429.       .414
```

Table A5-22

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS

Case 8

```
                        CHAMBER                         TOTAL
   NOZZLES/SQ FT        LENGTH      UNITS/SERIES        LENGTH      NOZZLE PSI
        6.0              8.0            2.0             36.0          15.0
GPM/NOZZLE
     2.000        2.500       3.000        4.000        5.000

                      UNIT COSTS FOR SCRUBBER SYSTEM
POWER        MAINTENANCE        NOZZLES        AMORTIZATION
$/KWH        $/SQRT(CFM)         $ EA             FACTOR
 .025          8.000            5.000              .130

FLOW RATE    CONCENTRATION      HENRY      SCHMIDT NO      TEMPERATURE
   CFM       INLET  OUTLET                                 DEGREES F
 25000.      2000.   20.          0.            0.               70.

             INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST   CAPITAL   TIM-SEC   HEIGHT   GPM/NOZ    FT2/FT3   NO      N1
     32372.      55146.      1.2      5.7       2.0       8.2 1378867 1301741
      32372.
     32297.      53360.      1.1      5.3       2.5       8.7 1359509 1271013
      32297.
     32267.      52056.      1.0      5.1       3.0       9.2 1343894 1244991
      32267.
     32279.      50266.       .8      4.7       4.0       9.9 1319620 1202042
     32338.      49088.       .7      4.4       5.0      10.6 1301093 1166955
     32267.      52056.      1.0      5.1       3.0       9.2 1343894 1244991
      32267.


              OPERATING CONDITIONS OF TOWER-CALCULATED
          THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
     SCRUBBER WIDTH      SCRUBBER HEIGHT      TOTAL FLOW RATES
          FEET                FEET            GAS(CFM)    LIQUID(GPM)
           5.1                 5.1            25000.0           460.5

     NOZZLES/BANK        BANKS/UNIT       DDROP UM       UNITS/SERIES
         154.                1.             439.                2.

          PRESSURE DROP       FAN HORSEPOWER        PUMP HORSEPOWER
                3.000             21.409              12.700


                CHEMICAL CONSUMPTION
                CAUSTIC         CHLORINE
                LB/YEAR         LB/YEAR
                129143.           84014.


                CAPITAL COSTS FOR SCRUBBER SYSTEM
 SHELL       NOZZLES       FAN      PUMP      MOTORS        TANKS       EXTERNALS        TOTAL
23664.       1535.         519.     1298.     2458.          5885.      16697.            52056.

                   ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION     POWER    MAINTENANCE     CHEMICALS     TOTAL     $/1000CFM-HR
    6767.        3492.     1789.            20219.      32267.          .323
```

Table A5-23

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 9

```
                        CHAMBER                          TOTAL
   NOZZLES/SQ FT        LENGTH     UNITS/SERIES          LENGTH     NOZZLE PSI
       6.0                8.0           3.0              52.0          15.0
GPM/NOZZLE
    2.000       3.000       3.500       4.000       5.000

                        UNIT COSTS FOR SCRUBBER SYSTEM
POWER       MAINTENANCE        NOZZLES        AMORTIZATION
$/KWH       $/SQRT(CFM)         $ EA             FACTOR
 .025          8.000           5.000              .130

FLOW RATE    CONCENTRATION      HENRY     SCHMIDT NO      TEMPERATURE
   CFM       INLET   OUTLET                                DEGREES F
 25000.      2000.   20.         0.           0.                70.

            INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST   CAPITAL   TIM-SEC   HEIGHT   GPM/NOZ   FT2/FT3  NO   N1
     31357.     63494.      1.4       4.9       2.0      6.3 1053200 1018011
      31357.
     31257.     60127.      1.1       4.4       3.0      7.0 1026487  981020
      31257.
     31262.     59049.      1.0       4.2       3.5      7.3 1016510  966436
     31286.     58200.      1.0       4.1       4.0      7.6 1007946  953531
     31365.     56951.       .8       3.8       5.0      8.1  993795  931338
     31257.     60127.      1.1       4.4       3.0      7.0 1026487  981020
      31257.


                 OPERATING CONDITIONS OF TOWER-CALCULATED
             THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
       SCRUBBER WIDTH       SCRUBBER HEIGHT      TOTAL FLOW RATES
            FEET                  FEET          GAS(CFM)     LIQUID(GPM)
            4.4                   4.4           25000.0          351.8

       NOZZLES/BANK       BANKS/UNIT       DDROP UM       UNITS/SERIES
           117.               1.             439.               3.

            PRESSURE DROP       FAN HORSEPOWER       PUMP HORSEPOWER
                  4.500           32.114              9.587


                 CHEMICAL CONSUMPTION
                 CAUSTIC        CHLORINE
                 LB/YEAR        LB/YEAR
                 107122.          69118.


                 CAPITAL COSTS FOR SCRUBBER SYSTEM
  SHELL      NOZZLES      FAN      PUMP      MOTORS       TANKS       EXTERNALS        TOTAL
 26715.      1759.        519.     1643.     3125.        7510.        18857.          60127.

                       ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION     POWER   MAINTENANCE     CHEMICALS     TOTAL    $/1000CFM-HR
    7816.        4541.    2191.           16708.       31257.        .313
```

Table A5-24

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 10

```
                       CHAMBER                           TOTAL
   NOZZLES/SQ FT       LENGTH     UNITS/SERIES           LENGTH     NOZZLE PSI
        6.0             8.0           2.0                 36.0          15.0
GPM/NOZZLE
     2.000        2.500        3.000        3.500        4.000

                     UNIT COSTS FOR SCRUBBER SYSTEM
POWER       MAINTENANCE        NOZZLES         AMORTIZATION
$/KWH       $/SQRT(CFM)        $ EA               FACTOR
  .025         8.000           5.000               .130

FLOW RATE    CONCENTRATION     HENRY     SCHMIDT NO     TEMPERATURE
   CFM       INLET  OUTLET                               DEGREES F
  50000.      500.   10.        0.            0.              70.

             INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST   CAPITAL   TIM-SEC   HEIGHT   GPM/NOZ   FT2/FT3  NO    N1
     31398.      89902.      1.1      7.6      2.0       7.4 1241072 1184231
      31398.
     31336.      87230.      1.0      7.1      2.5       7.8 1223648 1158313
      31336.
     31337.      85279.       .9      6.8      3.0       8.3 1209594 1136456
     31375.      83783.       .8      6.5      3.5       8.6 1197837 1117441
     31434.      82596.       .8      6.3      4.0       8.9 1187745 1100537
     31336.      87230.      1.0      7.1      2.5       7.8 1223648 1158313
      31336.


                 OPERATING CONDITIONS OF TOWER-CALCULATED
             THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
        SCRUBBER WIDTH      SCRUBBER HEIGHT       TOTAL FLOW RATES
              FEET                FEET          GAS(CFM)    LIQUID(GPM)
               7.1                7.1           50000.0          764.2

        NOZZLES/BANK      BANKS/UNIT      DDROP UM      UNITS/SERIES
            306.              1.            425.             2.

             PRESSURE DROP      FAN HORSEPOWER      PUMP HORSEPOWER
                   3.000          42.818              21.977


                   CHEMICAL CONSUMPTION
                   CAUSTIC       CHLORINE
                   LB/YEAR       LB/YEAR
                    75672.         41600.

                   CAPITAL COSTS FOR SCRUBBER SYSTEM
 SHELL      NOZZLES      FAN      PUMP      MOTORS       TANKS      EXTERNALS       TOTAL
36521.      3057.        849.     1741.     3693.         7974.      33395.          87230.

                        ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION     POWER  MAINTENANCE    CHEMICALS    TOTAL    $/1000CFM-HR
    11340.       6458.   2530.          11008.      31336.        .157
```

Table A5-25

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 11

```
                    CHAMBER                        TOTAL
   NOZZLES/SQ FT    LENGTH    UNITS/SERIES     LENGTH    NOZZLE PSI
         6.0          8.0          3.0         52.0        15.0
GPM/NOZZLE
     2.000      2.500      3.000      3.500      4.000

                     UNIT COSTS FOR SCRUBBER SYSTEM
POWER       MAINTENANCE      NOZZLES      AMORTIZATION
$/KWH      $/SQRT(CFM)        $ EA          FACTOR
  .025        8.000          5.000         .130

FLOW RATE    CONCENTRATION    HENRY    SCHMIDT NO    TEMPERATURE
   CFM       INLET  OUTLET                           DEGREES F
  50000.      500.   10.       0.          0.               70.

                INTERMEDIATE VALUES DURING OPTIMIZATION
   ANNUAL COST  CAPITAL  TIM-SEC  HEIGHT  GPM/NOZ  FT2/FT3  NO  N1
      33594.    103232.     1.3     6.6      2.0      5.6  946424  920724
       33594.
      33539.    100310.     1.1     6.2      2.5      6.0  933137  903500
       33539.
      33553.     98189.     1.0     5.9      3.0      6.3  922419  889142
      33607.     96573.      .9     5.7      3.5      6.6  913453  876770
      33684.     95299.      .9     5.5      4.0      6.8  905758  865857
      33539.    100310.     1.1     6.2      2.5      6.0  933137  903500
       33539.


                    OPERATING CONDITIONS OF TOWER-CALCULATED
                THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
      SCRUBBER WIDTH      SCRUBBER HEIGHT      TOTAL FLOW RATES
            FEET                 FEET          GAS(CFM)    LIQUID(GPM)
             6.2                 6.2           50000.0          582.8

      NOZZLES/BANK      BANKS/UNIT      DROP UM      UNITS/SERIES
          233.              1.            425.               3.

            PRESSURE DROP      FAN HORSEPOWER      PUMP HORSEPOWER
                  4.500         64.227             16.417


                    CHEMICAL CONSUMPTION
                    CAUSTIC       CHLORINE
                    LB/YEAR       LB/YEAR
                     60836.         34219.


                    CAPITAL COSTS FOR SCRUBBER SYSTEM
 SHELL      NOZZLES     FAN     PUMP     MOTORS      TANKS     EXTERNALS      TOTAL
41187.      3497.       849.    2206.    4691.       10166.     37714.        100310.

                     ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION    POWER   MAINTENANCE    CHEMICALS    TOTAL    $/1000CFM-HR
    13040.      8465.   3098.           8935.    33539.          .168
```

Table A5-26

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 12

```
                    CHAMBER                        TOTAL
   NOZZLES/SQ FT    LENGTH    UNITS/SERIES     LENGTH    NOZZLF PSI
        6.0           8.0          3.0         52.0        15.0
GPM/NOZZLE
     2.000      2.500      3.000      4.000      5.000

                    UNIT COSTS FOR SCRUBBER SYSTEM
POWER       MAINTENANCE      NOZZLES      AMORTIZATION
$/KWH       $/SQRT(CFM)       $ EA           FACTOR
  .025         8.000         5.000           .130

FLOW RATE    CONCENTRATION    HENRY    SCHMIDT NO    TEMPERATURF
  CFM        INLET  OUTLET                             DEGREES F
  50000.     2000.   20.        0.          0.               70.

          INTERMEDIATE VALUFS DURING OPTIMIZATION
  ANNUAL COST  CAPITAL  TIM-SEC  HEIGHT  GPM/NOZ   FT2/FT3  NO  N1
     59064.    107740.     1.4     7.0     2.0      6.3 1053236 1018043
      59064.
     59017.    104593.     1.2     6.6     2.5      6.7 1038450  997911
      59017.
     59044.    102308.     1.1     6.3     3.0      7.0 1026522  981051
     59204.     99194.     1.0     5.8     4.0      7.6 1007981  953560
     59430.     97168.      .8     5.4     5.0      8.1  993829  931366
     59017.    104593.     1.2     6.6     2.5      6.7 1038450  997911
      59017.


               OPERATING CONDITIONS OF TOWFR-CALCULATED
          THE MATERIAL OF CONSTRUCTION IS STAINLFSS STEEL
     SCRUBBER WIDTH     SCRUBBER HEIGHT     TOTAL FLOW RATES
          FEET               FEET          GAS(CFM)    LIQUID(GPM)
           6.6                6.6          50000.0          648.5

     NOZZLES/BANK      BANKS/UNIT      DDROP UM      UNITS/SERIES
        259.               1.             425.             3.

          PRESSURE DROP      FAN HORSFPOWFR       PUMP HORSEPOWFR
                4.500         64.227               18.381


               CHEMICAL CONSUMPTION
               CAUSTIC       CHLORINF
               LB/YEAR       LB/YFAR
               214245.        138237.


               CAPITAL COSTS FOR SCRUBBER SYSTEM
 SHELL     NOZZLES    FAN     PUMP     MOTORS     TANKS     FXTERNALS      TOTAL
44057.     3891.      849.    2349.    4892.      10840.     37714.        104593.

                    ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION    POWER   MAINTENANCE    CHEMICALS   TOTAL   $/1000CFM-HR
   13597.       8905.   3098.           33417.     59017.       .295
```

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 13

```
                    CHAMBER                        TOTAL
  NOZZLES/SQ FT    LENGTH    UNITS/SERIES     LENGTH    NOZZLE PSI
        6.0          8.0          2.0          36.0        15.0
GPM/NOZZLE
     2.000      2.500      3.000      3.500     4.000

                   UNIT COSTS FOR SCRUBBER SYSTEM
POWER      MAINTENANCE      NOZZLES       AMORTIZATION
$/KWH      $/SQRT(CFM)       $ EA            FACTOR
 .025         8.000         5.000            .130

FLOW RATE    CONCENTRATION     HENRY    SCHMIDT NO     TEMPERATURE
   CFM       INLET  OUTLET                               DEGREES F
 100000.      500.   10.        0.          0.                70.

               INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST   CAPITAL   TIM-SEC   HEIGHT   GPM/NOZ   FT2/FT3   NO     N1
     58528.     155855.     1.1      10.7      2.0      7.4 1241115 1184268
      58528.
     58550.     151526.     1.0      10.1      2.5      7.8 1223691 1158349
     58659.     148363.      .9       9.6      3.0      8.3 1209636 1136491
     58817.     145937.      .8       9.2      3.5      8.6 1197879 1117474
     59002.     144011.      .8       8.9      4.0      8.9 1187787 1100569
     58528.     155855.     1.1      10.7      2.0      7.4 1241115 1184268
      58528.


                 OPERATING CONDITIONS OF TOWER-CALCULATED
            THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
     SCRUBBER WIDTH      SCRUBBER HEIGHT      TOTAL FLOW RATES
          FEET                 FEET          GAS(CFM)    LIQUID(GPM)
          10.7                 10.7          100000.0        1383.4

     NOZZLES/BANK      BANKS/UNIT       DDROP UM      UNITS/SERIES
         692.              1.              409.            2.

          PRESSURE DROP       FAN HORSEPOWER       PUMP HORSEPOWER
                3.000            85.636              42.122


                 CHEMICAL CONSUMPTION
                 CAUSTIC       CHLORINE
                 LB/YEAR       LB/YEAR
                 151345.          83199.


                 CAPITAL COSTS FOR SCRUBBER SYSTEM
 SHELL      NOZZLES       FAN       PUMP       MOTORS        TANKS       EXTERNALS       TOTAL
61092.      6917.       1413.      2465.      5793.        11386.       66790.        155855.

                    ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION    POWER   MAINTENANCE    CHEMICALS    TOTAL    $/1000CFM-HR
    20261.     12673.    3578.          22016.     58528.        .146
```

Table A5-28

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 14

```
                       CHAMBER                           TOTAL
   NOZZLES/SQ FT       LENGTH     UNITS/SERIES           LENGTH     NOZZLE PSI
         6.0            16.0            2.0              52.0           15.0
GPM/NOZZLE
      1.000        1.500       2.000       2.500       3.000

                        UNIT COSTS FOR SCRUBBER SYSTEM
POWER       MAINTENANCE        NOZZLES        AMORTIZATION
$/KWH       $/SQRT(CFM)          $ EA            FACTOR
 .025          8.000           5.000            .130

FLOW RATE     CONCENTRATION      HENRY       SCHMIDT NO      TEMPERATURE
  CFM         INLET   OUTLET                                  DEGREES F
 100000.       500.    10.          0.            0.                70.

               INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST   CAPITAL    TIM-SEC    HEIGHT    GPM/NOZ    FT2/FT3   NO      N1
     58793.     177682.       2.6      11.6        1.0       4.8 1029280   992016
      58793.
     57929.     166055.       2.1      10.4        1.5       5.4 1003182   956217
      57929.
     57547.     159029.       1.8       9.6        2.0       5.9  985062   928886
      57547.
     57381.     154213.       1.6       9.0        2.5       6.2  971233   906788
      57381.
     57329.     150659.       1.4       8.6        3.0       6.6  960078   888066
      57329.
     57329.     150659.       1.4       8.6        3.0       6.6  960078   888066
      57329.

                 OPERATING CONDITIONS OF TOWER-CALCULATED  ,
            THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
     SCRUBBER WIDTH       SCRUBBER HEIGHT       TOTAL FLOW RATES
          FEET                  FEET           GAS(CFM)     LIQUID(GPM)
            8.6                  8.6          100000.0          1316.0

     NOZZLES/BANK        BANKS/UNIT        DROP UM        UNITS/SERIES
          439.                 1.             439.                2.

            PRESSURE DROP        FAN HORSEPOWER          PUMP HORSEPOWER
                 3.000              85.636                 38.614

                 CHEMICAL CONSUMPTION
                 CAUSTIC       CHLORINE
                 LB/YEAR       LB/YEAR
                 151345.          83199.

                 CAPITAL COSTS FOR SCRUBBER SYSTEM
 SHELL       NOZZLES       FAN       PUMP       MOTORS        TANKS        EXTERNALS        TOTAL
59016.       4387.       1413.      2394.      5611.        11049.        66790.          150659.

                    ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION     POWER    MAINTENANCE     CHEMICALS     TOTAL     $/1000CFM-HR
    19586.       12150.    3578.            22016.      57329.          .143
```

Table A5-29

DESIGN AND COST CALCULATIONS FOR SPRAY SCRUBBERS
Case 15

```
                    CHAMBER                         TOTAL
   NOZZLES/SQ FT    LENGTH   UNITS/SERIES      LENGTH    NOZZLE PSI
         6.0         16.0         2.0          52.0         15.0
GPM/NOZZLE
     1.500     2.000     2.500     3.000     3.500

                 UNIT COSTS FOR SCRUBBER SYSTEM
POWER     MAINTENANCE      NOZZLES     AMORTIZATION
$/KWH     $/SQRT(CFM)       $ EA          FACTOR
 .025         8.000         5.000          .130

FLOW RATE   CONCENTRATION   HENRY   SCHMIDT NO   TEMPERATURE
  CFM       INLET  OUTLET                          DEGREES F
 150000.     500.   10.      0.          0.            70.

           INTERMEDIATE VALUES DURING OPTIMIZATION
  ANNUAL COST  CAPITAL  TIM-SEC  HEIGHT  GPM/NOZ  FT2/FT3  NO  N1
     83653.    229779.    2.1     12.7     1.5     5.4 1003203  956234
      83653.
     83258.    220502.    1.8     11.7     2.0     5.9  985082  928903
      83258.
     83132.    214143.    1.6     11.0     2.5     6.2  971252  906804
      83132.
     83146.    209452.    1.4     10.5     3.0     6.6  960097  888082
     83240.    205818.    1.3     10.0     3.5     6.8  950765  871738
     83132.    214143.    1.6     11.0     2.5     6.2  971252  906804
      83132.


             OPERATING CONDITIONS OF TOWER-CALCULATED
          THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL
    SCRUBBER WIDTH     SCRUBBER HEIGHT     TOTAL FLOW RATES
         FEET               FEET          GAS(CFM)    LIQUID(GPM)
         11.0               11.0          150000.0        1819.7

    NOZZLES/BANK      BANKS/UNIT      DDROP UM      UNITS/SERIES
         728.             1.             425.             2.

          PRESSURE DROP     FAN HORSEPOWER     PUMP HORSEPOWER
               3.000          128.455            55.659


              CHEMICAL CONSUMPTION
              CAUSTIC       CHLORINE
              LB/YEAR       LB/YEAR
              227017.        124799.


              CAPITAL COSTS FOR SCRUBBER SYSTEM
 SHELL     NOZZLES     FAN     PUMP     MOTORS     TANKS     EXTERNALS     TOTAL
81193.     7279.     1912.    2896.    7258.     13421.      ******      214143.

                ANNUAL COST FOR SCRUBBER SYSTEM
AMORTIZATION   POWER   MAINTENANCE    CHEMICALS   TOTAL   $/1000CFM-HP
   27839.      17887.   4382.          33024.    83132.       .139
```

Appendix 6

MASS TRANSFER AS A FUNCTION OF PACKING DEPTH

MASS TRANSFER AS A FUNCTION OF PACKING DEPTH

In tests 31 and 32, two stages of alkaline sodium hypochlorite were tested. Each stage contained 2 ft of packing. The Number of Mass Transfer Units (NTUG's) for each test were calculated, and the average NTUG's computed:

Test No.	Inlet ED_{50}	Outlet ED_{50}	NTUG*
31-1	700	25	3.33
31-2	15,500	45	5.84
31-3	590	45	2.57
32-1	21,500	15	7.26
32-2	2,700	35	4.35
32-3	5,000	450	2.41
32-4	19,000	300	4.15
32-5	16,000	240	4.20
Average	10,000	140	4.26

In test 33, alkaline sodium hypochlorite was tested in a one-stage scrubber, containing 4 ft of packing. The average NTUG is calculated below:

Test No.	Inlet ED_{50}	Outlet ED_{50}	NTUG*
33A	15,000	680	3.09
33A	15,000	20	6.62
33B	4,300	350	2.51
33B	4,300	60	4.27
Average	9,650	277	4.12

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* $$\text{NTUG} = \ln \frac{\text{Inlet } ED_{50}}{\text{Outlet } ED_{50}}$$